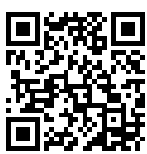
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ELECTRONS, ELECTRIC WAVES AND WIRELESS TELEPHONY

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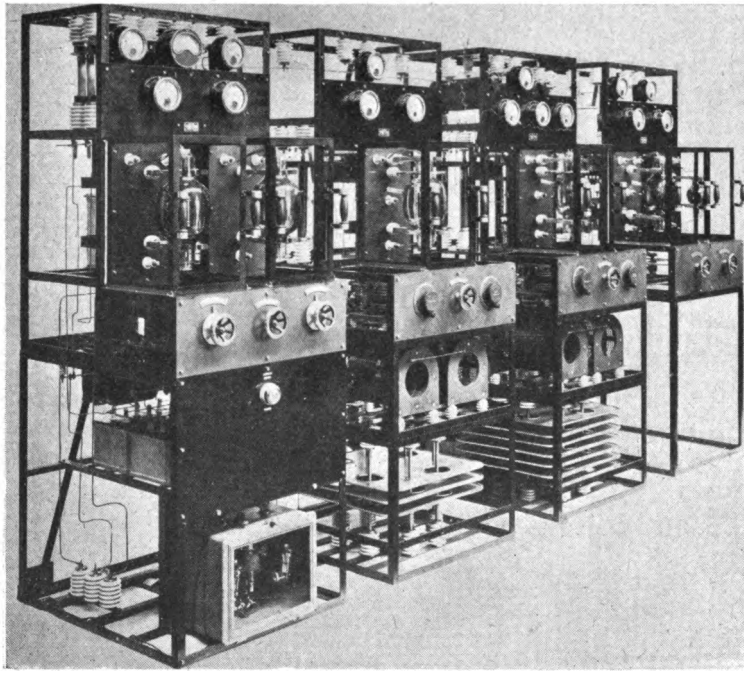
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Broadcasting apparatus, with thermionic valve transmitters, designed by the Marconi Company.

Frontispiece.

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ELECTRONS, ELECTRIC WAVES AND WIRELESS TELEPHONY

BY

J. A. FLEMING, M.A., D.Sc., F.R.S.

UNIVERSITY PROFESSOR OF ELECTRICAL ENGINEERING IN THE UNIVERSITY OF LONDON.
HONORARY MEMBER OF THE INSTITUTION OF ELECTRICAL ENGINEERS, LONDON.
HONORARY MEMBER OF THE ROYAL ENGINEERS' INSTITUTE, CHATHAM.
ALBERT MEDALLIST OF THE ROYAL SOCIETY OF ARTS, LONDON.
MEMBER OF THE ROYAL INSTITUTION OF GREAT BRITAIN.
VICE-PRESIDENT OF THE RADIO SOCIETY OF GREAT BRITAIN. HONORARY MEMBER OF THE ASSOCIATION OF ENGINEERS. LIEGE, BELGIUM.

BEING A REPRODUCTION WITH SOME AMPLIFICATION OF THE CHRISTMAS LECTURES (96th COURSE) DELIVERED AT THE ROYAL INSTITUTION OF GREAT BRITAIN, DECEMBER, 1921, JANUARY, 1922

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FOREWORD

THE present little book is a reproduction, with some amplification, of the Course of Christmas Lectures given by the author at the Royal Institution of Great Britain, London, in December, 1921, January, 1922. This course was the ninety-sixth in the series of annual juvenile lectures instituted by Faraday in 1826, and was the fourth which the author has had the privilege of giving in that series.

The book gathers together also the articles which have appeared in serial form in *The Wireless World* and *Radio Review* during the five months, October, 1922, to February, 1923, on the subject of "Electrons, Electric Waves and Wireless Telephony."

The great public interest in this topic drew very large audiences to the above-mentioned lectures, and, indeed, the theatre of the Royal Institution was not sufficiently spacious to hold all those who desired to attend.

Hence it has seemed probable that a reproduction in book form would be acceptable to many others not able to be present.

Even though published lectures are devoid of the

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interest attaching to discourses illustrated copiously by experiments, and in spite of the already abundant literature on this subject, it is hoped that the explanations given may be useful to radio amateurs and others who are not merely intent on " listening in " to broadcasted music or speech, but desirous also of understanding a little of the mode in which these achievements of wireless telephony are accomplished. The story of the invention and development of the thermionic valve and its applications in public radiotelephony is one of the fairy tales of science, and the study of it brings the student into contact with some of the most interesting problems of physical science.

J. A. F.

University College, London,
March, 1923.

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ELECTRONS, ELECTRIC WAVES AND WIRELESS TELEPHONY

CHAPTER I

SURFACE WAVES AND WAVE PRODUCTION

NOW that the wonderful art of wireless telephony has reached a point in its development at which it has become a popular pastime in place of an exceptional feat by experts, and when regular broadcasting and the sale of receiving apparatus has made it possible for every one to take part in it, there is naturally a demand for expositions of the scientific principles underlying it, which shall be capable of being understood by the general reader.

This is not adequately supplied either by the highly technical journals or by the bulk of the popular wireless literature. Mere pictures or even semi-technical explanations of the mysteries of receiving circuits or the mode of employing thermionic valves or crystals for "listening in," do not entirely meet the public requirements.

This remarkable achievement of applied science is the outcome of the great advances which have taken place in the last quarter of a century in our knowledge concerning atoms, electrons, electric waves and electrical physics generally.

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An intelligent comprehension of the *modus operandi* of the technical appliances used in wireless telephony necessitates, then, some slight acquaintance with modern scientific views concerning the nature of matter and electricity, and the possible relations of these to the more fundamental conceptions of æther, space, time and energy.

Probably the chief gain which will result from a keen popular interest in wireless telephony will be an increased public attention to the progress of electrical science. In view of recent important advances in pure science, many explanations in our text-books on electricity require to be re-written.

In the present little book an attempt will be made to give in outline an account of some of these modern ideas, and advances in recent physics, as far as they bear on the evolution of wireless telephony. The highly technical details of wireless apparatus and its expert management will not so much concern us, and, in any case, is provided for in other publications and books.

When any one not in the least acquainted with the facts of electrical physics asks a wireless operator to explain the nature of his operations and appliances, he is generally informed it is accomplished by the use of "electric waves." But any attempt to progress beyond the stage of mere phrases generally places the expert and the questioner in difficulties.

To answer this question at all efficiently renders it necessary to build up from a deeper foundation

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and consider in detail what is meant in scientific language by the term *wave*. It is essential, therefore, to start from a consideration of familiar physical effects which can be seen with the bodily eyes, and to make of these stepping-stones, by which we may be enabled to understand something of analogous processes which can only be appreciated with the eyes of the mind.

1. Surface Waves on Liquids.

The easiest avenue of approach to the study of waves in general is to discuss some of the properties and the nature of the visible surface waves on liquids. We are all acquainted with the appearance of the sea surface when it is traversed by and tossed up into waves, and also with the effects produced on the surface of still water when it has ripples created upon it by the splash of a stone thrown in. In common language we apply the term "wave" to the splashing water thrown up on the beach or rocks at the seaside (Fig. 1). This, however, is merely the result of the break-up or end of a wave, and in a scientific sense of the word it is not more properly called a wave than a house in the act of falling down could be described as a "desirable residence."

To understand what is meant by a surface wave in scientific terminology we must go out a little distance from the coast over deep sea water on some breezy day. We shall then see what appear to be rounded elevations or hummocks on the water,

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which move forward. To the inexperienced eye it seems as if the surface water, as a whole, was in motion in one direction.

If, however, we fasten attention upon some floating object, such as a patch of seaweed or a sea-gull sitting on the water, we see that as each wave passes under it the floating object is merely lifted up, pushed forward a little, then let down and drawn

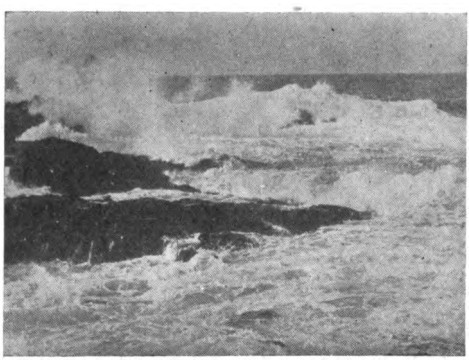


FIG. 1.—Sea waves breaking on the rocks and beach.

back, and, in short, never moves far from one position. A little thought makes it evident we have to distinguish between the motion of the water particles *per se*, and the motion or change in position of the elevations and depressions in the water surface.

We can watch with the eye the progress of a certain hump or ridge on the surface, but that hummock does not consist of the same particles of water for two successive instants.

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At any one spot the actual extent of the displacement of individual particles of water may be small, and the progressive movement is merely the apparent change in place from instant to instant of the locality at which this displacement or motion is a maximum or minimum. A simple illustration of the effect may be obtained by laying transversely upon a long horizontal board a cardboard cylinder about the same length as the width of the board. To this cylinder is attached a string, by which it can be pulled along parallel to itself. Over the cylinder

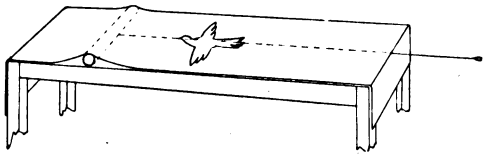


FIG. 2.—A model to explain the progression of a surface wave on water.

is laid a strip of green cloth which must be taken to represent the sea surface. A small piece of paper, cut out in the shape or a seagull or a small stuffed bird, may then be pinned to the cloth (see Fig. 2). If, then, the card roller is pulled along under the cloth each point of the latter will be successively raised and lowered. A moving elevation of the cloth in the form of a ridge or hummock will travel along the cloth and initiate by its action on the model bird the behaviour of the water at one point and at various points in the path of the wave.

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2. Definition of Wave Motion.

We are then able to give a definition of wave-motion as follows :—

If the particles of any material or parts of any construction perform successively, meaning by that one after the other and not all at once, any kind of movement or displacement in which they start from and come back to a given point, this constitutes a *wave motion*. We can see this process illustrated when a gust of wind blows over a field of ripe corn. Each ear or row of ears along a certain region bows down under the pressure of the wind, and then springs up again. Row upon row of the cornstalks successively make their obeisance in this fashion to Hermes, and the result is that a sort of shadow sweeps over the field, very beautiful to behold, which constitutes a kind of wave.

A wave does not necessarily involve motion. It may consist in any kind of cyclical change repeated from point to point along a certain line. Thus, suppose we have a very long row of incandescent electric lamps, which by some contrivance can be switched on one at a time for a moment, and then off again. If each lamp in turn, one after the other, progressively along the row, is thus illuminated for an instant, we shall see a wave of illumination propagated along the series of lamps. This effect is, in fact, seen in many electric light advertising signs in public streets by night.

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If at each point in the series the motion or change is only performed once, we have a so-called *solitary wave*. If at each point it is repeated at regular intervals we shall have produced a *train of waves*.

We can provide an illustration of a progressive wave train in the following way. Wind a length of stiff wire round a pencil or other circular sectioned rod in open turns, like a corkscrew. Fix this spiral in a frame (see Fig. 3) so that it can be rotated. Throw the shadow of it on a screen by means of an optical lantern or else the sunlight, and rotate the screew. The shadow will present the appearance of a series of waves travelling along. If a little bit of sealing wax is put on the screw at one point its shadow will merely move up and down on the screen, thus enabling us to distinguish between the cyclical motion at each point in the system, and the apparent motion of the wave.

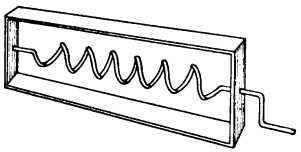


FIG. 3.—A spiral wire, the shadow of which when the wire is rotated imitates a series of progressive waves.

When dealing with trains of waves there are four terms very frequently in use which it will be convenient to define at this stage.

At any one point in the wave region the material or medium executes a certain regularly repeated motion, or else some cycle of operations. The number of times this cycle is repeated per second or per unit of time, is called the *wave frequency*. The

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greatest extent of this displacement or motion, or other change from its zero position, is called the *wave amplitude*.

The shortest distance measured across from one wave hump or maximum to the next adjacent one is called the *wavelength*. It is important for the general reader to notice that the term "a long wave" does not mean a wave which is long in the direction of the crest, ridge, hump or elevation, but it means that distance between the waves is relatively large. Thus, for instance, if we pleat a sheet of paper, so that the folds or ridges are close together, we might take this as an illustration of what is meant by "short" waves. If, however, the ridges or pleats are relatively far apart, they would be called "long" waves (see Fig. 4).

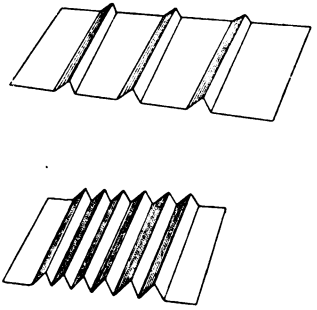


FIG. 4.—Pleated paper models to illustrate the difference between "long" and "short" surface waves on water.

The terms "long" and "short" are, however, relative, and what would be a very long wave for certain purposes might be a very short one for others.

Then, in the next place, every wave moves forward parallel to itself with a certain speed called the *wave velocity*. We may, for instance, imagine a

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bird to fly along over the sea surface in the same direction in which the waves are travelling, and to keep himself always poised above the same crest or hump. The speed with which the bird flies is then the same as the wave velocity.

In all cases of wave motion there is a connection between the wave velocity, the wave frequency and wavelength, as follows:—*The wave velocity is numerically equal to the product of the wavelength and wave frequency when using the same units of length and time.* Thus, if the water at any place rises and falls ten times a minute, and if the shortest distance from crest to crest or the wavelength is 20 ft., then the wave velocity is $10 \times 20 = 200$ ft. per minute.

In many cases the velocity of the wave is quite independent of the wavelength, that is, long and short waves travel at the same speed. This is the case with wireless waves, and those similar waves which constitute light. On the other hand, it is not the case with surface waves on liquids. On the deep sea surface long waves travel faster than short waves.

Approximately speaking, in the case of deep sea waves the wave velocity is about equal to the square root of $2\frac{1}{4}$ times the wavelength. Thus, waves on the Atlantic Ocean, which are spaced apart 300 ft. from crest to crest, or have a wavelength of 100 yards, travel at about 26 miles an hour, or roughly at the speed of a slow railway train. Hence, they catch up a not very quick-moving ship, and passing under it cause the ship to pitch.

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3. Production of a Wave.

We must next consider a little more carefully how a wave is produced, and why it travels along when once started.

In order that a true self-propagating wave may be produced on or in a material, the latter must possess two special properties.

First, it must have elasticity of some kind; that is, it must *resist* some kind of change in it, for example, compression, twisting, stretching, or rotation, and must spring back when released.

Secondly, it must *persist* in motion or have mass or inertia, or some quality equivalent to it which causes it to store up energy when moving, or as the displacement is changing. In short, the medium must possess the power of storing up energy in two ways, viz., as potential energy in the form of some strain, or displacement, and as kinetic energy in the form of some motion, or other change not purely mechanical but equivalent to motion or release of strain.

At any one point the energy is being transformed periodically from potential to kinetic form and back again In a wave motion, in which the motion or displacement follows a simple harmonic law, the average of the varying potential energy during one complete period is equal to the average of the varying kinetic energy during the same period.

The mode of production of a compressional wave

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can be studied by means of a simple model made with a number of golf balls suspended from a frame by strings so as to hang in a row, each ball being about two inches apart. The balls are inter-connected by spiral springs of brass wire, which resist compression or extension (see Fig. 5). If then the end ball is given a sudden blow with a piece of wood in the direction of the row of balls, it is set in motion and its kinetic energy expended in compressing the spring between it and the second ball. Owing to the mass or inertia of the balls the compression is not transmitted instantly to all the springs, but the spring between the balls 1 and 2 after being compressed expands again and brings ball 1 to rest and starts ball 2 in motion. This again compresses the spring between ball 2 and ball 3, and the same process is repeated from ball to ball. The movement and compression is thus handed on, and finally reaches the end spring and ball, which latter flies off freely.

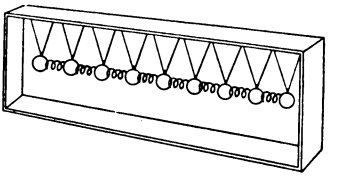


FIG 5.—A model made with golf balls and spiral springs to illustrate the nature of a longitudinal wave.

It is easy to watch the rather slow propagation of this wave of compression along the row of balls. As an illustration of another kind of wave called a distortional wave, a model of the following description can be made.

Stretch in a long frame a pair of parallel steel

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wires about half an inch apart. Thread on these wires long slips of wood or metal (see Fig. 6). The steel wires, and therefore the bars threaded on them, resist being twisted relatively to each other. Hence, if we give the end bar a transverse pull so as to twist the wires between the bar 1 and bar 2, that twist will then tend to bring bar 1 back to its original place; but, having mass, it overshoots the mark and then the reverse twist applied pulls back bar 2. Each bar then continues to vibrate, but the vibrations of each bar are a little out of step with those of its neighbours on either side The vibratory motion is passed on from bar to bar with a certain delay in phase, as it is called, and hence we have a wave of distortion transmitted along the collection of bars strung on the steel wires.

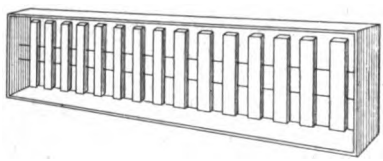


FIG. 6.—A model made with wooden bars and steel wires to illustrate the nature of a distortional wave.

There can be as many different types of wave as there are kinds of elastic resistance, and in a solid elastic substance it is possible to have two types of wave produced, one called a compressional wave in virtue of the fact that the solid resists compression, and the other called distortional in consequence of the fact that a solid resists change of shape. We have these two kinds of waves produced in the earth's crust during earthquakes.

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4. Waves on Water.

In the light of these explanations we can then consider the familiar facts connected with the production of waves when a stone, for instance, is thrown upon still water in a lake.

We know that a free water surface is a level

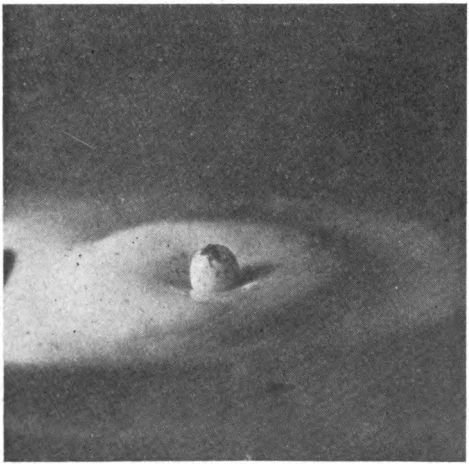


Fig. 7.—An instantaneous photograph of a ball dropping into water and creating a circular wave of elevation on it.

surface and that the water resists being made unlevel, and if it is momentarily heaped up or depressed at any place the force of gravitation at once restores the level.

When a stone is thrown on water and plunges downward through the surface, it creates a temporary depression or cavity in the water. Since

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water is nearly incompressible, it follows that if the surface is depressed at one place it must be heaped up in some adjacent place. Therefore the plunging stone not only creates a cavity, it also heaps up the water in a circular ridge or hummock all round the depression (see Fig. 7). But this state of the water cannot continue if left to itself. The water rushes



FIG. 8.—A train of expanding circular ripples on water created by throwing a stone into a pond.

in to fill up the central cavity and its inertia carries it up into a column or hump. This involves the production of a ring-shaped depression or trough around the elevation and the first-formed annular ridge or elevation, is pushed farther out. The water at the splash point thus bounces up and down, say half a dozen times before it comes to rest, and this creates as many concentric ring-shaped ridges and

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troughs on the surrounding surface, which then expand outwards as a family of wavelets or ripples (see Fig. 8).

There is one curious fact connected with this ripple band which few persons out of the thousands who throw stones into water have ever noticed. On looking carefully at the ever-expanding band of ripples it will be noticed that on the inner edge little wavelets are continually being produced and others die away at the outer edge. In other words, the waves travel through the band of wavelets faster than the group of waves moves as a whole. This establishes an important distinction between the velocity of *a* wave and the velocity of a *group* of waves.

In the case of wireless waves there is no difference between the wave velocity and the group velocity, but for sea waves or the surface of deep water the group velocity is half the velocity of the single wave.

The waves on a water surface produced by throwing in a stone or other object, or by the wind, as in the case of sea waves, are called *gravitation waves*, because the elastic resistance called into play is that due to the effort of the water surface to remain level under the action of gravitation.

5. Capillary Surface Waves.

We can, however, produce another type of wave on a water surface called a *capillary wave*, which

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depends upon the resistance of the water surface to stretching.

The surface of every liquid is in a state in which the surface particles draw each other together or cling more closely than those in the interior. Hence a certain effort or force is necessary to break through the surface film or to stretch it, and this surface layer endeavours always to contract or shrink up to the smallest area consistent with the boundary conditions. This is called the *surface tension* of the liquid or the *capillarity*. This last term is derived from the Latin word for a hair, because the ascent of liquids in very fine tubes such as the sap in a tree up the fine tubular tissues is due to this same action. The ascent of a liquid up a fine tube is dependent upon the condition that the liquid must wet the walls of the tube.

The existence of this surface film upon liquids and its resistance to stretching gives the explanation of the fact that small bodies made of material intrinsically heavier than water can yet float upon it. If a little very clean water is put into a clean saucer, a fine clean steel sewing needle can be dropped upon the surface if held in a horizontal position close over it and released, and it will then be seen to float on the water. The needle is not heavy enough to break through the surface film, but makes a little depression in it, in which the needle lies like a baby in its cradle. It is for this reason that small dust particles can lie on water and little insects can

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run over the surface without risking death by drowning.

We can produce capillary waves on water by holding vertically and half immersed in it a straight stiff fine wire and pushing the wire quickly forward across the surface. Round the point of immersion of the wire will be seen a group of very small waves or ripples which become of shorter wavelength in proportion as the wire is more quickly moved forward.

Again, when drops of water such as raindrops fall on the surface of pools of water, each drop as it strikes the surface creates a rapidly expanding ring-shaped ripple, which is a capillary wave. These are instances of waves on water which depend not upon gravitation but upon capillarity for their formation.

The fact that a liquid film is in a state of tension and tries to contract as much as possible is easily proved by experiments with soap bubbles. If a soap bubble is blown on the end of a glass tube and the mouth then removed from the blowing end, the bubble begins at once to shrink up, exactly as a thin indiarubber balloon would do if inflated with air and then left to itself. Another similar experimental proof is as follows :—Make a wire ring about 2 ins. in diameter, having a long wire handle, and tie across the ring a fine thread, which is not drawn quite tight. Fill the ring with a soap film by immersing it in a soap solution in such fashion that the loose thread is entirely wetted by and included

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in the film. Then break through the film on one side of the thread, and the liquid film tension on the other side will at once contract and pull the thread tight into the form of a curve, which then forms one boundary of the film. We see by this experiment that a liquid film is in a state of stretch or tension, and will always contract so as to make its surface area as small as is consistent with the boundary conditions. Hence it resists stretching, and in virtue of this can have capillary or surface tension waves formed on it. There is one distinction between these two types of surface water wave which should be noted.

We have already explained that on deep water long gravitation waves travel faster than short ones. On the other hand, short capillary waves move faster than long ones. There is, therefore, a certain wavelength for surface waves on water, about two-thirds of an inch in length, at which surface waves travel at the slowest rate, viz., about 9 ins. a second.

This wave may be considered to lie on the boundary, between true gravitation waves, which are longer, and true capillary waves, which are shorter than this critical length.

6. Experimental Illustrations of Wave Phenomena.

There are several ways in which the phenomena of wave motion can be rendered visible to the eye and

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studied in detail, but owing to the speed with which waves and ripples move over the surface of liquids special means are necessary to bring the effects within our powers of vision. One of these is to take instantaneous photographs of the waves either in bright sunlight or else by the flash light of an electric spark. Some very interesting photographic studies were made of ripples on the surface of mercury many years ago by Mr. J. H. Vincent, who published and described his experiments in the *Philosophical Magazine* for June, 1897, September, 1898, and October, 1899. His method of creating these waves consisted in attaching a small needle of steel to the prong of a tuning fork kept in vibration, and allowing the point to touch the surface of a layer of mercury (quicksilver) in a shallow dish. The vibration of the prong sets up ripples on the mercury surface which flit away rapidly from the point. By taking instantaneous photographs of the ripples by the flash of an electric spark he was able to secure views of the state of the surface at any instant.

Fig. 9 shows two of his photographs. The left-hand one gives a view of the concentric system of ripples expanding outwards from one centre of disturbance. The right-hand photograph shows the interlacing ripples produced by two centres of disturbance. Each set of ripples moves outwards from its centre independently of the other set.

It is possible with another type of apparatus to exhibit many interesting experiments with capillary

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FIG. 9.—Instantaneous photographs of ripples set up on a mercury surface when agitated by the vibrations of a tuning fork (J. H. Vincent).

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waves on water which illustrate the properties of waves in general. As arranged by the author for lecture purposes to a larger audience this apparatus is as follows :—A circular shallow trough is constructed, having a plate-glass bottom and an exit tap. The trough may be about 8 ins. in diameter, and should be fitted with an overflow tube so as to keep a constant depth of about $\frac{1}{2}$ or $\frac{3}{4}$ of an inch of water in it. This trough is placed on the stage of a vertical projection electric lantern, so that light is sent through it, and an image of any object on the surface of the water is focussed on the lantern screen. The trough is provided with a pair of fine supply tubes, by means of which drops of water coming from an elevated tank can be allowed to drop at regular intervals on the water surface in the shallow tank. As each drop falls on the water it will start a ring-shaped capillary ripple, but this ripple flits outwards so rapidly the eye cannot follow it. We can, however, render it visible as follows. In front of the lantern objective we place a metal disc with 4 or 6 holes in it. The disc must be caused to rotate by a pulley and belt, so that as it revolves it periodically eclipses, and allows the light from the lantern to pass as in a cinema projector lantern. The result is that the image on the screen is seen intermittently. If, now, the rate at which the water drops fall on the water surface is so adjusted that the interval between two drops falling is equal to the interval between the passage

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of two holes in the disc in front of the lantern objective lens, we shall see on the screen an image of a set of concentric annular ripples, which will appear to be stationary or can be made to expand slowly outwards by properly adjusting the speed of the stroboscopic disc.

With this apparatus we can show a number of instructive experiments. If we arrange two dropping tubes so as to drop water at places an inch or two apart in the tank, and adjust the drops so that they fall simultaneously, then we shall see on the screen a complex pattern of ripples. Each set of drops makes its own concentric set of annular wavelets. It will then be clear that at certain places the humps of one set of waves will coincide with the humps of the other set, and the elevation of the water at those places will be increased. In the same way the hollows or depressions of one set will be in coincidence with those of the other, and will increase the depression. On the other hand, there will be some places lying along certain lines at which the humps or crests of one set of waves will coincide with the hollows or troughs of the other, set, and hence at these places the waves will extinguish or nullify each other. This effect is called the *interference* of waves, and is of great importance in wave phenomena in general (see Fig. 10). In fact, whenever we can obtain evidence of interference we can say with almost complete certainty that we are dealing with a case of wave motion.

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In our lantern tank experiment the lines along which interference is taking place from waves diverging from two centres are lines which are parts of curves called hyperbolas, because it is a property of such a curve that the difference of the distance of any

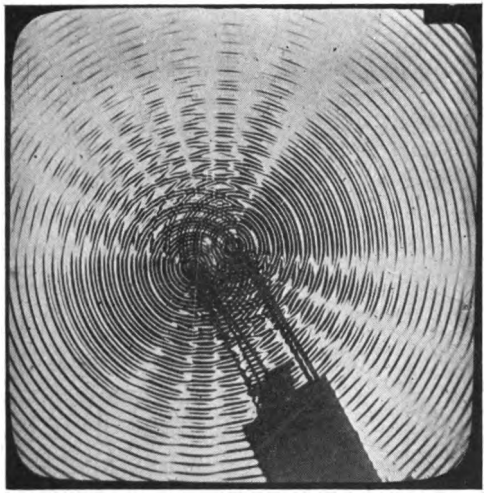


FIG. 10.—The interference of two sets of circular ripples on a mercury surface. The white portions in the diagram are the places in which the two sets of waves have interfered and destroyed each other. This diagram is a reproduction from an instantaneous photograph taken by Mr. J. H. Vincent.

point on the curve from two fixed points called the foci in constant. The condition of interference is that the distance of the point at which it takes place from the two wave sources must be a certain odd multiple of half a wavelength, and, moreover, the waves must start in the same phase at the same instant from the two sources.

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Another effect well shown by this ripple apparatus is the reflection of a wave. For this purpose we put into the shallow trough a little flat wall of metal which stands up a little above the water. The dropping point is arranged at a little distance from this wall so that the miniature waves strike against it like sea waves on the coast striking a sea wall. We then see on the screen a double set of ripples, one set approaching the wall, and another set moving away from it. This second set appears to diverge from a point as far behind the wall as the actual source point is in front of it. The reason for this will be evident on looking at the diagram in Fig. 11.

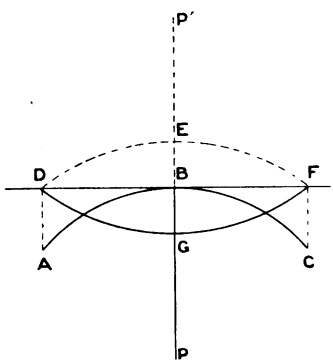


FIG. 11.

Let *P* be the origin from which the waves diverge and let *A B C* represent the crest of one annular wave just reaching the wall *D B F*. If the wall did not exist that wave would move onwards, and an instant later would be found in the position *D E F*, which is part of a circle whose centre is at *P*. Since, however, all parts of the wave *A B C* are turned back or reversed in motion on striking the wall, the actual reflected wave is found at *D G F*. It is obvious that this is part of a circle whose centre is at *P'*,

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which is a point as far behind the wall *D B F* as the actual origin *P* is in front of it. The actual process of reflection of the wave is as follows :—

Consider one circular crest *A B C* (see Fig. 12), which is advancing to the wall *D F*. As each point on that wave reaches the wall it will create a vibration in the water, which causes a secondary wave to diverge in circles from that point. Thus,

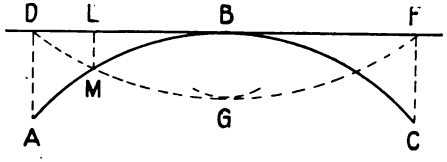


FIG. 12.

when the front of the wave touches the wall at *B*, a circular wave begins to diverge from *B*. A little later a point *M* on the wave reaches the wall at *L*, and from that point another secondary disturbance originates. Similarly, when a point *A* on the original wave reaches the wall at *D*, it gives rise to a secondary wave diverging from that point. The wave originating at *B* gets the start over that originating at *L* and that at *L* over the wave starting from *D*.

The line *D G F* (dotted) which touches all these

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secondary waves at any instant is called their *envelope* and is the resultant reflected wave. Everyone knows that in the case of a reflected image in a looking glass, the image of the object appears to be as far behind the mirror as the real object is in front of it. This is simply a consequence of the fact that the reflected image is caused by light which diverges in spherical waves of a certain kind from every point on the object, and the observer into whose eyes these reflected rays enter sees the image as a collection of radiant points, each of which appears to be as far behind the mirror as the corresponding radiant point in the object is in front of it.

Many optical illusions and conjurers' tricks depend upon this principle. Thus, for instance, we can easily create the illusion of a candle appearing to burn inside a decanter of water as follows :—

Set up vertically on a table a very clean sheet of clear plate-glass and place a lighted candle at a place near it. The candle can be shaded by a little screen so as not to be seen directly but only as a reflected image in the glass surface. This image appears to be behind the glass. At that point place a large glass decanter full of water and when looked at from a certain direction, the illusion will be complete of a candle appearing to burn inside a bottle of water (Fig. 13).

Another important property of surface waves

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and of waves in general can be demonstrated by the same apparatus, viz., the refraction of waves.

If we have a set of parallel plane or straight waves which are moving in one material or medium and advancing in an inclined direction to a straight boundary between that medium and one in which

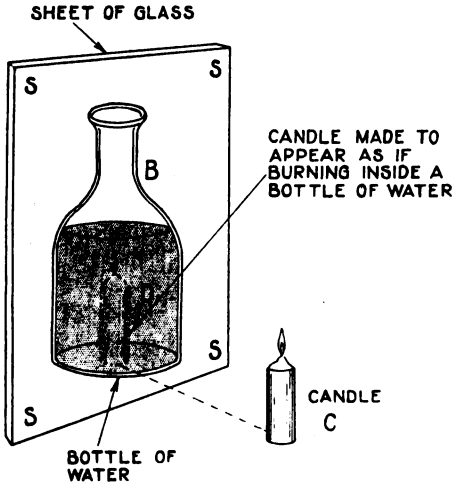


FIG. 13.

the waves move with a different velocity, then on crossing the boundary the direction in which the waves are advancing is changed. Thus, let *A B* be the crest line of a straight wave advancing parallel to itself towards a boundary line *D F* between two media 1 and 2. Let us suppose that the waves travel more slowly in medium 2 than in medium 1. Then when the left-hand end *A* of the wave *A B*

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passes the boundary it will proceed more slowly (Fig. 14). Hence it will only have reached a point *C* and travelled a distance *A C* in the time that the right-hand end *B* will have travelled over a greater distance *B D* and reached the point *B*. Therefore the line of the wave front, viz., *A B*, will be slewed round into *C D* on crossing the boundary into the position *D C*. This is called the *refraction* or bending of a wave.

It is this bending of the wave front when passing across the boundary of two media in which the wave has different velocities which determines so many familiar optical phenomena such as the apparent bending of a stick when placed half immersed in an inclined position in water.

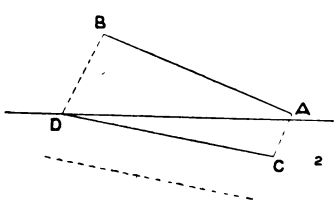


FIG. 14.—A diagram illustrating the refraction of a wave.

The refraction of ripples can be shown with the above-described lantern apparatus as follows :—

A semi-circular thick sheet of glass is provided which fits into the lantern tank and makes one half of it more shallow than the other. One dropping tube is arranged so as to send out ripples from a point in the deeper part of the tank. These ripples spread out in circular rings. If the water level is adjusted so that over the shallow part of the tank it has a very slight depth, not more than a milli-

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metre or so, then over this part the ripples will travel more slowly than over the deeper portion. Hence, when the ripples pass over the boundary line it will be seen, on regulating the speed of the stroboscopic disc as above described, that there is

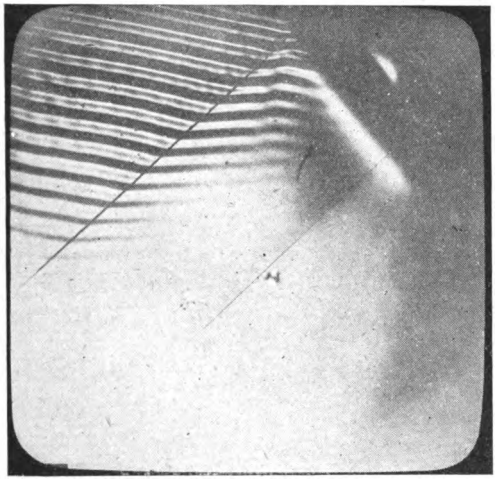


FIG. 15.—A reproduction of an instantaneous photograph taken by Mr. J. H. Vincent, showing the refraction or bending of waves in passing over from one part of a mercury surface to another in which they have a different velocity of propagation.

a discontinuity or change of direction of the expanding annular ripples. On the shallow part the form and curvature of the ripples is such that they appear to diverge, not from the actual dropping point, but from another point situated a little way from it. The illustration in Fig. 15 shows this

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effect very well in the case of ripples on a mercury surface photographed by Mr. J. H. Vincent.

7. Waves Produced by Ships.

In connection with this part of our subject, attention may be directed to a very important class of surface waves on water, viz., those made by

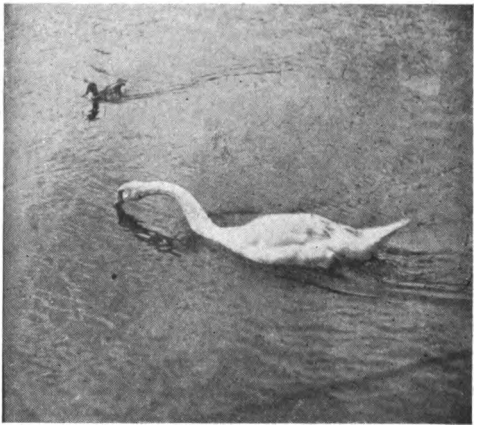


Fig. 16.—Echelon waves on water produced by the motion of a swan.

ships, boats, and aquatic animals in moving over the surface.

If we look at any swan or duck swimming on a pond, especially if the bird is moving quickly, we shall see a set of ripples on either side of it, each comprising a number of wavelets set one behind the other and all included between two lines, starting from the bird's breast, which are inclined to one

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another at an angle of 38° 56′. These little wavelets overlap and are said to be arranged "in echelon," a term derived from the French word *échelle*, for steps like a ladder (see Fig. 16).

They are probably best seen when a boy's model ship is sailing over smooth water on a pond, and it

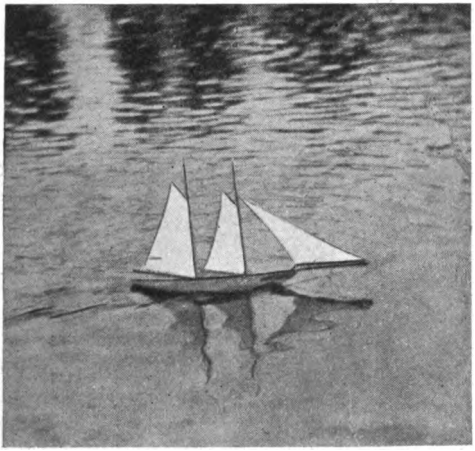


FIG. 17.—Echelon waves on water produced by the motion of a boy's model ship.

will then be noticed that in addition to the echelon waves, which start from the bows, there is another set of transverse waves behind the ship. In fact, the echelon waves and transverse waves all form part of one complete system of ship waves (see Fig. 17).

This system of waves above mentioned is all included between two inclined lines, which start from

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the ship's bows. A construction which gives this angle is as follows:—Describe a circle and draw through its centre *C* a diameter *A B*. Produce this line *A B* to a point *S*, such that the length *B S* is equal to *A B*. Then from the point *S* draw two lines, called tangents, to touch the circle at points *D* and *E*. Then the angles *D S B*, *E S B*, are

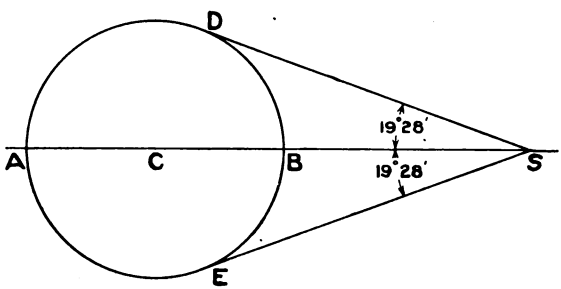


FIG. 18.

each 19° 28′, and the angle *D S E* is 38° 56′ (see Fig. 18).

Let us consider for a moment how these waves are formed. When the ship moves forward through the water it gives a push to the water which creates an elevation and starts a wave. This push being continually repeated as the ship progresses creates a group or family of waves. One of these waves may be considered to be attached to the ship's bows, and to move forward with it. It has already been pointed out that in the case of surface waves on water the velocity of a group of waves is half that of

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a single wave. Hence, if when the ship is at *A* it starts a group of waves, the middle point of this group will have travelled only as far as *B* by the time that the ship itself, carrying one wave with it, has travelled double that distance and arrived at *S*. Hence we see that a ship moving over the water is followed by an ever lengthening train of waves, the group velocity of which is half that of the ship.

The subject of wave production by ships is of enormous practical importance, because the creation of waves absorbs or requires an expenditure of energy. In the case of a stream, petrol or electric ship that energy is derived from the coal, petrol or other source of driving power. Hence, other things being equal, the less the ship makes waves the less the dissipation of energy. Great attention has therefore been given to the design of ships' hulls with the object of determining what form has the least wave-making quality.

All the power taken up in wave-making travels away from the ship and is wasted, and hence to obtain the greatest speed for the least expenditure of propelling power, the form of the ship must be such as to create surface waves as little as possible.

In addition to the power absorption in wave-making there is also an expenditure in making eddies or little vortices in the water, and at low speeds the chief source of energy waste is in over-

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coming frictional resistance between the water and the hull of the ship.

This last can be reduced by making the hull smooth, and also free from projecting studs or rivet heads, all of which also tend to create eddies in the water and increase the skin resistance and, therefore, energy loss. It is now the custom to predetermine the effects of any proposed form or design of ship hull on the power required to drive it through the water at a given speed by means of experiments made on large scale models dragged through the water in a very long tank called a testing tank. The models are made to scale in paraffin wax, as this material can easily be shaped to any required form and then melted down and used over again.

The model is then dragged through the water in tank at a given speed, and by means of a sensitive recording dynamometer the power exerted is exactly measured.

As the subject of ship design is not one with which we are here concerned the mode of conducting these tank experiments need not be discussed. The reader who desires more information may be referred to the author's book, "Waves and Ripples in Water, Air, and Aether" (published by the S.P.C.K.), or to Lord Kelvin's "Popular Lectures and Addresses," Vol. III (Macmillan & Co.), see the "Lecture on Ship Waves."

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8. Rotational and Irrotational Fluid Motion.

There is one point in connection with the motion of liquids to which it may not be amiss to make a brief reference. A liquid is capable of motion in two ways, one of which is called *irrotational* motion and the other *vortex* motion.

In the irrotational motion every particle of the liquid moves without rotation. If we imagine any small spherical portion of the liquid to become solidified, and that we could make a mark on this little solid sphere, and watch it as it moves with all the rest of the liquid, we should find the marked spherule moving so as always to keep its marked end pointing in one constant direction. In other words, although it may possess a progressive motion, it is not revolving in any way, or has no rotational motion. On the other hand, if the motion of the liquid is such that the selected spherule turns round continually so as to face in different directions as it progresses, and as the moon does in revolving round the earth, then the motion is called rotational. If the liquid particles rotate so as always to face towards a certain line, called a vortex line, then this motion is called vortical.

We can see a vortex of water formed every time we pull up the waste-plug of a bath or wash-hand basin full of water. The water swirls round, forming what is called a whirlpool or eddy, or vortex, in

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which a certain part of it is revolving round an axis rotationally. A vortex in a liquid must either have its two free ends on the liquid surface or else it must form an endless vortex or vortex ring.

We can see the former type of vortex formed by drawing a teaspoon, with the bowl half immersed, quickly through a cup of tea. On the edge of the

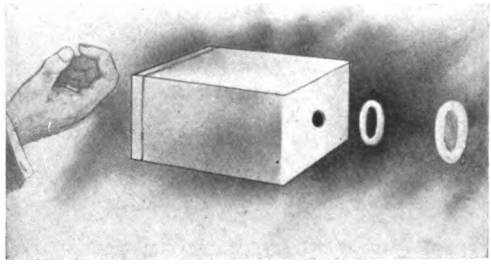


FIG. 19.—Smoke rings or circular vortex rings produced by tapping the back of a paper box filled with smoke and making their exit out of a hole in the front.

spoon will be noticed two little whirlpools of liquid which move with the spoon. These are the ends of a vortex which extends from one whirlpool to the other round the edge of the immersed part of the spoon.

On the other hand, we see an endless vortex produced in those smoke rings which many cigarette smokers can blow from the mouth or end of the cigarette.

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In this case the smoky air is revolving round a circular or closed line in such fashion that the motion on the inside of the ring is in the direction in which the ring as a whole is moving forward.

They can be better made as follows :—Make a little cubical paper box of rather stiff paper, the side of which may be 3 or 4 ins. in length. Cut the circular hole about 1 or $1\frac{1}{2}$ ins. in diameter in the centre of one side (Fig. 19). Fill the box with tobacco smoke by puffing a cigarette into it. Then give a smart tap on the side of the box opposite to the hole. A smoke ring will emerge and fly through the air. A careful examination of the ring as it moves will reveal the peculiar kind of rotary motion which is taking place in the ring. The smoke merely makes evident the air motion, but the vortex ring is produced and exists when the box is tapped, whether it is full of smoke or not. We have such vortex rings produced whenever a jet of gas or liquid moves through an undisturbed mass of gas or liquid.

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CHAPTER II

WAVES IN AIR

9. Compressional Waves in Air.

WE have in the next place to explain the nature of a wave which is created *in* a material, and not simply *on* the surface of a medium. To follow this explanation necessitates some effort of the power of mental vision, because objective perception is more difficult or impossible.

As already mentioned, there are two types of wave which can thus be produced, viz., compressional and distortional waves, depending upon the two kinds of elastic resistance which can be offered.

A *solid* is defined as a material which offers resistance to change of shape as well as to change of bulk or size. An elastic solid is one which, when slightly changed in shape or size, returns exactly to its original shape or size when the deforming force is removed.

A *liquid* or *gas* is matter in a physical state in which it offers elastic resistance to change of bulk or volume, but little or no resistance to change of shape.

The elastic resistance to change of volume is called volume elasticity; and the substance is said

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to have compressional elasticity or compressibility. The resistance to change of shape is called rigidity, and a substance which possesses elastic resistance to change of shape is said to have distortional elasticity.

In scientific language any change of size or shape in a substance is called a *strain*, and the corresponding force causing it is called a *stress*. Elasticity is numerically measured by the ratio of stress to strain in appropriate units. Hence in scientific language a substance is called highly elastic if it requires a relatively large stress or force to make a given small strain. In common language we generally say that a substance, for example, indiarubber, is very elastic if it stretches a great deal under a small pull; but in scientific usage we call a substance such as steel highly elastic because it requires a very large stress or force to create a relatively small strain, or stretches very little under a pull. The strain is always measured by the ratio of the change in volume or length to the original volume or length.

The two types of elasticity with which we are concerned in wave propagation are the volume elasticity and the simple rigidity or shape elasticity.

Before discussing the way in which these qualities affect the speed of wave propagation it may be well to consider in detail the process of producing a space wave or wave *in* an elastic medium such as air.

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Suppose a very sudden expansion of the air is made at one place by a little explosion or by an electric spark, the effect is to compress suddenly the air in a small spherical shell lying around that point. Owing to the inertia and compressibility of the air this compression does not make itself felt at once at any great distance. When the explosion is over, this shell of compressed air immediately around the place of explosion expands again, and in so doing compresses the air in a spherical shell just outside the first layer. This again, in turn, releases itself, and so the compression is handed on from layer to layer. If we picture to ourselves the region round the original centre of explosion as divided into concentric shells like the coats of an onion, we can say that each shell in turn becomes compressed and then expanded again, passing from within outwards. This gradual transference of the compression from layer to layer constitutes a wave of compression, and in air at the temperature of melting point of ice (0° Centigrade), it travels at the rate of 1,090 ft. per second or nearly 700 miles per hour.

It can be proved by mathematical reasoning, though the proof is not given here since it is somewhat difficult to follow, that the speed at which a wave travels in an elastic medium is numerically equal to the square root of the quotient of the elasticity by the density, using the appropriate units.

In a gas such as air the decrease in volume

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produced by an increase in pressure is such that if the pressure is applied slowly the product of volume and pressure remains constant.

For those readers who can follow an argument in algebraic symbols it can be stated as below.

Let V be the original volume and let v be a small reduction in volume produced by an increase in pressure from P to $P + p$. Then by the above rule (Boyle's Law) we have—

$$(V - v)(P + p) = VP \text{ or}$$

$$P = \frac{V - v}{v} p = \frac{p}{v/V}$$

provided v is small compared with V. But $\frac{p}{v/V}$ is the ratio of increase in pressure to decrease in volume expressed as a fraction of original volume. This is, therefore, the compressional elasticity. Accordingly this last is numerically equal to the pressure of the gas at standard temperature 0° Centigrade. But the law of Boyle only holds good for changes of pressure so slowly applied that no change of temperature takes place.

In the case of the compression produced in air waves, the pressure is suddenly applied and it can be shown that the elasticity with which we are then concerned is measured, not by the pressure P but be 1·41 times P.

To render the above explanations clearer we may consider a numerical example.

The pressure of the air at normal barometric

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height is about $14\frac{1}{2}$ on the square inch and is equal to the pressure of a column of mercury in the barometer, 760 millimetres or nearly 30 inches high. It is also about 2116·4 pounds per square foot. But the so-called weight of 1 lb. is 32·2 absolute units of force in British foot, pound, second units; because a mass of 1 lb. acquires under gravity a velocity of 32·2 feet per second per second, whereas the unit force imparts a velocity of only 1 foot per second per second. Hence the pressure per square foot in absolute units of force is $2116{\cdot}4 \times 32{\cdot}2 = 68{,}148$. If we multiply this number by 1·41 we obtain the product 96088·68, which is the numerical value of the elasticity of air at 0° Centigrade and 760 mm. for suddenly applied pressure. The density of air at the same pressure and temperature is such that one cubic foot of air weighs 0·0807 pounds. Hence, if we divide the number 96088·68 by 0·0807 and take the square root of the quotient, we arrive at a number close to 1,090, which is therefore the velocity of a compressional wave in air at the above standard pressure and temperature in feet per second. In the case of water the ratio of elasticity to density is nearly 17 or 18 times that for air and the velocity of a compressional wave in water is therefore rather more than four times its velocity in air.

Although we cannot see these compressional waves in air they can nevertheless be photographed by an ingenious process which may be explained as follows :—

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If we look at a shallow pool of water on a bright sunny day, when there is a slight wind producing ripples on the surface of the pool, we shall see a series of bright lines on the bottom of the pool, which move with the wavelets. The curved surface of the wave makes the water act like a lens and concentrates the sun's light on certain lines, corresponding to these waves.

A wave in air is a region of condensation followed generally by one of rarefaction, and the compressed air acts to some extent like a lens on rays of light. Suppose, then, that we create a very sudden sound by means of the snap of an electric spark. This starts a sound wave which consists of a single region of compression followed by a region of expansion. This air wave can be allowed to flit across a sensitive photographic plate in a dark room. It moves at the rate of 13,200 inches or so per second, and therefore occupies about 1/2,000th part of a second in moving a distance of 6 inches.

Suppose a second electric spark is made at a distance from the plate, but so that its light falls on the plate. If the interval of time between the sound-creating spark and the light-creating spark is properly adjusted, the latter will impress on the photographic plate an image of the sound wave as it flits across the plate.

Some very successful experiments in photographing sound waves in this manner were carried out as far back as 1899 by Prof. R. W. Wood, and

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described by him in the *Philosophical Magazine* for August, 1899. He followed a method first used by Toepler, but with many improvements.

The light-giving spark was formed by the discharge of a small Leyden jar between two pieces of magnesium ribbon, clamped between two glass plates. An optical image of this spark was formed by a large lens, and the image nearly covered by a horizontal metal plate. Behind this was placed another lens which formed a faint image of the first lens on a photographic plate, which was thus uniformly illuminated. If, then, a sound wave produced by another electric spark, which takes place about one ten-thousandth part of a second before the light-giving spark is allowed to flit across the first lens, an image of the compressional wave in the form of a bright line appears upon the photographic plate when developed. We then see the compressional wave made by this spark as a circular ring-shaped image on the plate. If we allow the sound wave to impinge upon a reflecting surface we can see the reflected wave (see Fig. 20). We can in this way objectively inspect what takes place when compressional air waves are reflected or refracted in various ways.

Professor Wood was thus able to photograph air waves in the act of being reflected by plane surfaces or refracted by being transmitted through boxes, prisms or lenses of thin collodion, filled with gases such as hydrogen or carbon dioxide, in which com-

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pressional waves travel more quickly or more slowly than in air.

Although we cannot see these air waves with our eyes, we are provided with a pair of organs, our ears which are extraordinarily sensitive to compressional waves in air, either solitary or in trains, provided their wavelength lies within certain limits, viz., about 30 ft. and 2 or 3 ins.

These waves excite in our ears the sensation of sound. In the human being the external organ we commonly call the ear, is merely a wave collecting shell or sound

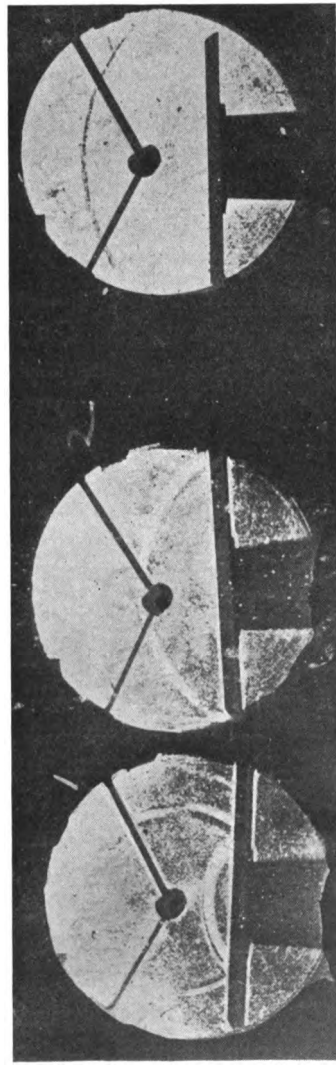


FIG. 20.—Photographs of sound waves produced by an electric spark between balls. The central black dots are the balls, and the inclined lines the wires leading to the two balls. The sound wave is shown reflected from a table, and the three views (left to right) show the various stages of the direct and reflected waves.

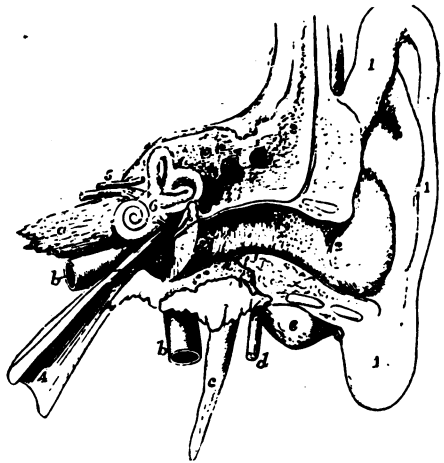
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catcher, and in animals, such as horses, dogs, cats, etc., it assumes the form of a curved flap or ear-trumpet capable of being turned in various directions.

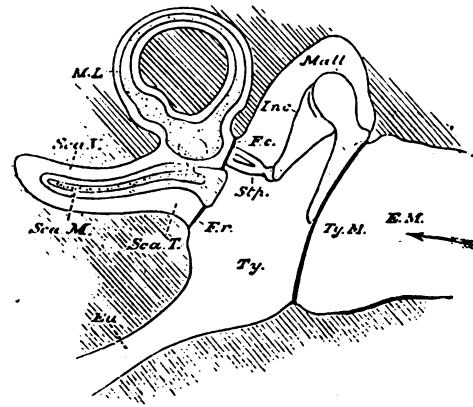
The true ear or actual organ of hearing is set deeply in the skull, and in mankind may be likened to a sort of house with two rooms and an entrance hall. The entrance hall is the tube opening into the external air. This is closed at the bottom by a delicate membrane like the wing of a fly, which is called the drum or tympanum. The first room of the ear, called the middle ear, is a cavity which is bounded on one side by the first tympanum and has on the other side two other inner tympana or drums. This cavity communicates with the back of the mouth by a canal called the Eustachian tube, which admits air to the middle ear (Fig. 21). The inner and outer tympana are connected by a little chain of bones called the ossicles. When a compressional wave from the outer air enters the external tube and strikes the ear-drum, it presses it in, and if the waves continue to arrive the tympanum will be set in sympathetic vibration.

These motions of the outer drum are communicated across the middle ear by the chain of bones, and act on the inner tympanum. Behind this middle chamber. and deeply buried in the bony framework of the skull, lies the real organ of hearing, in and by which the mere mechanical motions of the tympana are translated into sensations of sound.

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(*a*)



(*b*)

FIG. 21.—A sectional diagram of the human ear. 1. The external lobe. 2. The entrance channel. 3. The tympanum and middle ear. 4. The Eustachian tube. The chain of bones or ossicles connecting the tympana of the outer and inner ear cavities are shown in diagram (*b*).

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This inner ear contains an organ called Corti's organ, in which are spread out a vast number of nerve fibres which are extensions of the auditory nerve. It is in this inner chamber, the secrets of which physiologists have not yet been fully able to explore, that the transmutation takes place of physical motions into physiological perceptions, or sensations. The ear has a marvellous power of appreciating the frequency of the air waves which enter the outer ear, and also their amplitude, and in addition it detects that which is called their *wave form* or the degree of admixture of waves of different frequency and amplitude. The difficult questions of physiology and psychology involved in the explanation of the functions of the ear in hearing do not concern us here, but it is important to understand clearly the differences between the motions in the air itself which give rise respectively to sensations corresponding to musical sounds, to mere noises, and to articulate speech.

In an air wave there is a place or places at which the air is slightly compressed, due to the air molecules being a little crowded together, and other adjacent places where it is rarefied or the molecules less crowded together. These regions of compression and rarefaction are propagated or travel through the air, but the actual motion to and fro of the air molecules themselves at any one place which gives rise to these compressions or rarefactions is very small.

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The late Lord Rayleigh (third Baron) made experiments in 1877 in the open air on a calm day with a whistle giving out a sound or air wave having a frequency of 2,730. He found that such a whistle could be heard by a normal ear at a distance of 820 metres. The whistle was blown with a steady blast of air, and from the power required to blow it he was able to estimate that the amplitude of motion of the air particles in the sound wave at the above distance from the whistle was only 0·8 of one millionth of a millimetre. This is less than one twenty-five millionths of an inch. Yet the human ear is able to appreciate the extremely slight changes in air pressure due to the motion.

Lord Rayleigh also experimented in 1894 on the amplitude of the least audible sound waves given out by a tuning fork vibrating 256 times a second, and found it to be about 1·27 millionths of a millimetre.

It will be evident from these figures that the expenditure of energy necessary just to excite a sensation of sound in the ear is extremely small. Measurements made of the energy necessary just able to excite a sensation of light when entering the eye, show that the human eye and ear are about equally sensitive to radiant energy.

In order that an air wave may be produced it is therefore necessary for some solid body or else some puff of air to strike the stationary air very suddenly.

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When, for instance, we strike a gong with a drumstick, the disc of metal is pressed in at the centre by the blow, and this produces a sudden local compression of the air on the opposite side which starts an air wave. The actual extent of motion of the wave-producing device may be invisibly small. Thus, for example, if we strike the prongs of a tuning fork and so set them in vibration, the motion is not visible to the eye. If, however, we hold near to the prongs a little pith ball suspended by a silk thread the rapid bouncing to and fro of the ball reveals the minute vibratory motion of the prongs. In the same way, although we cannot see the motions of the disc of the sound-box of a gramophone when it is playing, we can feel that it is in motion by holding the finger very gently just in contact with the disc. Even in the case of loud sound the amplitude of the motion in the gramophone diaphragm scarcely exceeds a few thousandths of an inch.

10. Sound Waves.

The next question which must be answered is as to the nature of the motion of the air particles which takes place in sound waves. We have seen that it is an extremely minute motion to and fro in the direction in which the air wave is travelling.

If we suspend a weight from the end of a very long string, say 2 or 3 yards long, fixed at the upper end, and set the weight swinging, we have

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an arrangement called a simple pendulum. The motion of the bob backwards and forwards exactly resembles that of the end of a tuning fork emitting a pure musical sound, and it is called a simple harmonic motion. Let the bob of the pendulum be formed of a canister having a small hole in the bottom, and let the canister be filled with fine sand. As the pendulum vibrates the sand will run

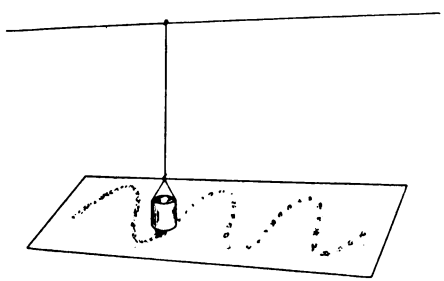


FIG. 22.—A pendulum having a bob delivering a stream of sand which marks a simple harmonic curve on a transversely moving strip of paper.

out of the hole in a fine stream. Let it fall on a long sheet of card (see Fig. 22). If the card is not moved the sand will be merely distributed in a long straight ridge. If, however, we move the card steadily and uniformly in a direction at right angles to that of the line of vibration of the bob the sand will be distributed in the form of a smooth wavy curve, called a simple harmonic curve (see Fig. 23).

We can imitate this curve in the following way. Procure a cardboard tube having a circular cross

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section and cut off the end obliquely with a sharp knife, so that the slanting end will touch everywhere a flat surface applied to it. Then fold a

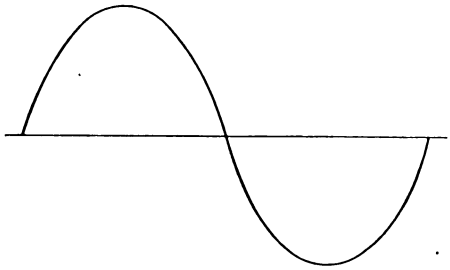


FIG. 23.—A simple harmonic or sine curve.

sheet of paper several times round the tube, and with scissors cut the edge of the paper to match the sloping end of the tube. Then unfold the paper and its edge will be found cut into the form of a simple harmonic curve (see Fig. 24).

Obtain if possible four tubes respectively of diameters, 3 ins., $1\frac{1}{2}$ in., 1 in., $\frac{3}{4}$ in., and prepare in the above manner from them four sheets of paper with their edges each cut in wavy curves of the above kind, but the distances from crest to crest of the humps will be in the ratio of 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$. By placing these templates, as they are called, on a sheet of paper and passing a pencil round the

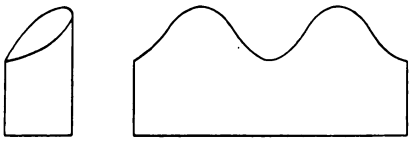


FIG. 24.—Method of forming a simple harmonic curve by a sheet of paper cut to fit round a cylinder with oblique end.

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curved edges, we can draw on the paper four simple harmonic curves which are said to have wavelengths in the ratio of $1 : \frac{1}{2} : \frac{1}{3} : \frac{1}{4}$ (see Fig. 25).

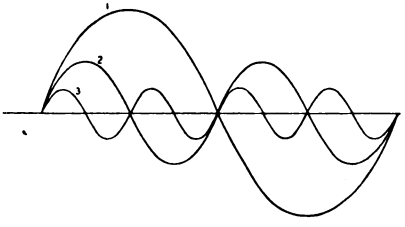


FIG. 25.—Simple harmonic curves with wavelengths in ratio of $1 : \frac{1}{2} : \frac{1}{4}$.

If we describe in this way, say, two superimposed simple harmonic curves with wavelengths in the ratio of 1 to $\frac{1}{2}$, we can then add together the heights of these two

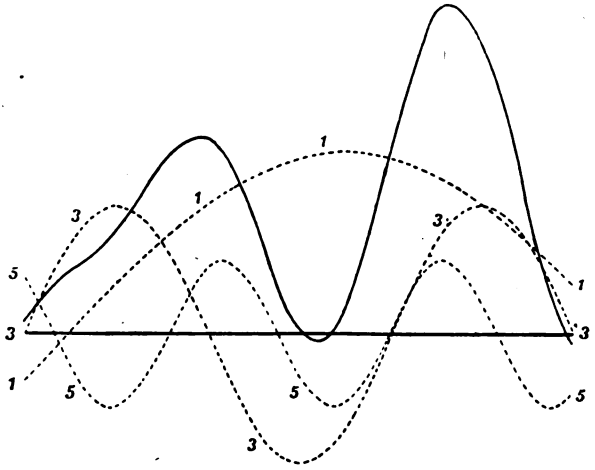


FIG. 26.—A diagram illustrating Fourier's theorem. The black firm line is a periodic curve, and the dotted lines its harmonic constituents with wavelengths in ratios $1 : \frac{1}{3} : \frac{1}{5}$.

curves above the mean line and obtain a third periodic curve which is said to be the sum of the

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other two. This third curve will be more irregular but will repeat itself (see Fig. 26).

In this way we can add together or sum a number of simple harmonic curves whose wavelengths are in the ratio $1 : \frac{1}{2} : \frac{1}{3}$, etc., and obtain very complex periodic curves which, however, repeat themselves in shape. Such curves are called complex periodic curves.

It is quite an easy thing to add together in this manner any number of simple harmonic curves of different wavelengths and amplitudes, and in any relative difference of phase; that means to say, shifted relatively to one another, but with the mean or centre lines of all the curves coincident, and thus obtain a complex curve.

11. Fourier's Theorem.

Strange to say, it is possible to perform the reverse operation, and if we are given a complex periodic curve which repeats itself regularly, we can discover the simple harmonic curves out of which it is built up. The fact that this can be done for certain periodic curves was first shown by a great French mathematician, Fourier, and it is in consequence called Fourier's theorem.

The importance of this fact in connection with sound and music is very great, because it shows us that simple musical sounds, such as those of a tuning fork or open organ pipe, when combined together, can produce air waves in which the to-and-fro motion of the air particles is very compli-

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cated and can only be represented by the varying height of a complex curve corresponding to various distances along its mean line taken as an axis of time. Also Fourier's theorem shows us that such sounds can be analysed into a number of pure musical sounds represented by simple harmonic curves.

Before proceeding further it will, however, be an advantage to explain the manner in which we can determine the nature of the motion of the air particles in air waves given out by various sound producing sources. This is accomplished by means of an instrument called a phoneidoscope, which is a word meaning "sound forms rendered visible."

It will perhaps be new to some readers to learn that every sound has a certain shape of wave form.

We recognise that there is a great difference between a mere noise and a musical sound, and also that there is a remarkable difference between the quality of the sound given by various musical instruments even when playing the same note. Also we know that in articulate speech there are great differences between the various vowel sounds, even when pronounced in the same tone and loudness.

The phoneidoscope enables us to ascertain the external or physical differences which correspond to these various kinds of sounds considered as sensations. It is constructed in the following manner (see Fig. 27) :—

A metal ring has clamped to it a circular disc of very thin glass or transparent mica. This disc is

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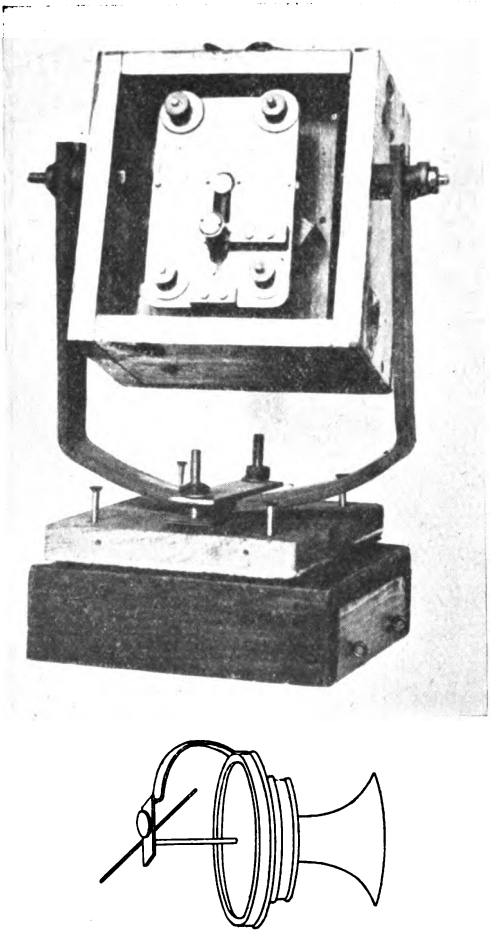


FIG. 27.—The phoneidoscope. (The lower diagram shows the mouthpiece, diaphragm and tilting mirror.)

best made about $2\frac{1}{2}$ in. in diameter, and the ring may be fixed at the narrow end of a wooden trumpet,

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like a gramophone horn. When an aerial wave enters this horn it presses the disc or diaphragm, as it is called, slightly outwards, and if aerial condensational waves continue to arrive, the disc is set in sympathetic vibration. To the centre of this disc is attached a small aluminium pin, cut with a chisel-shaped edge. This chisel presses on the underneath side of a small piece of celluloid, which is pivoted by a wire passed through its centre, and on the other side of the centre is a steel spring, which presses the celluloid up in the same direction as the pressure of the aluminium chisel. The little bit of celluloid has a small circular silvered glass mirror cemented to it. It will then be seen that if the mica disc moves to and fro or vibrates it will cause the little mirror to rock on its axis and the movements of this mirror will copy exactly the movements of the centre of the diaphragm. A ray of light is allowed to fall on this mirror and is reflected on to another steadily revolving mirror. The axis of revolution of this last mirror is so placed that if the diaphragm is at rest, the spot of light is carried horizontally across a screen, and in virtue of the persistence of vision, appears as a narrow line of light. If, however, vibrations of the mica diaphragm take place, the spot of light is caused to move up or down and the line of light becomes a more or less regular wavy line of light (see Fig. 28). With this apparatus we can try the following experiments.

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If we make near the horn any pure musical sound, we see the line of light thrown into a wavy line of simple harmonic wave form. If the sound is loud, the amplitude or height of these waves is large; but if the sound is feeble, the height is small.

Again, if we sound various notes from organ pipes or pitch-pipes, we find that if the sound is a low or bass note, the wavelength of the light line waves

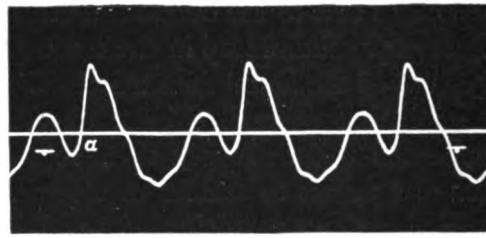


FIG. 28.—Wave form of a musical sound as rendered visible by the Phoneidoscope.

is large, but if the sound note is high or shrill, then the wavelength is small.

If we sing to the mica diaphragm various vowel sounds, *Ah*, *Ee*, *Ay*, etc., we find that the shape or wave form of the light line is different in every case. If we speak to the diaphragm or recite, the line is thrown into an irregular shape (see Fig. 29).

We see, therefore, that since the amplitude or extent of motion of the mica disc is a measure of that of the air particles which beat against it, we may conclude:

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(i.) That the amplitude of motion of the air particles determines the loudness of the sound;

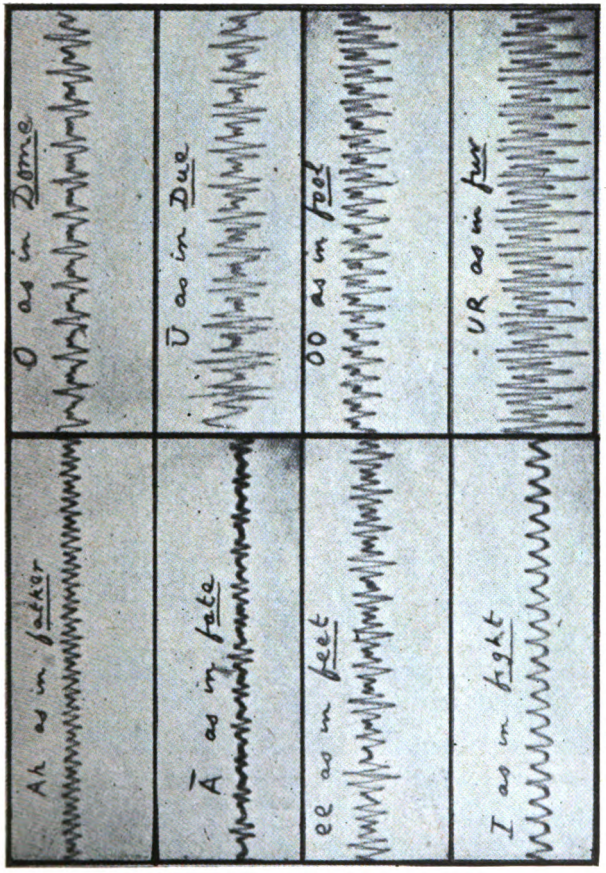


FIG. 29.—The wave forms or shapes of various vowel sounds as photographed by the Fleming Phoneidoscope.

(ii.) That the frequency of their vibration, or what comes to the same thing, the aerial

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wavelength, determines the pitch of the sound ; and

(iii.) That the wave form or sound shape of the

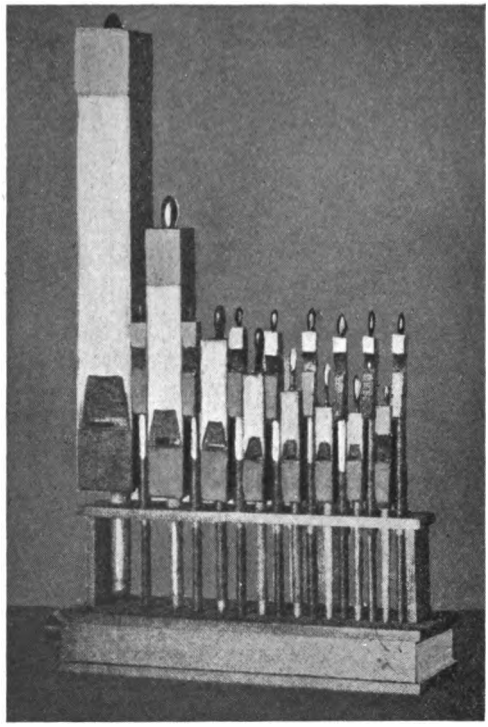


FIG. 30.—A collection of organ pipes which, when sounded together, emit the vowel sound *Ah*.

aerial vibrations determines the quality of the sound.

A musical sound results from regularly repeated aerial vibrations of a certain wave form. A mere

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noise results from irregular aerial vibrations, and articulate speech results from aerial vibrations of certain specialised forms.

Since the complex wave form of vowel sounds can be analysed into the sum of a number of simple or pure musical tones, it is possible to arrange a certain number of organ pipes to certain selected notes, such that when sounded together, they give out the vowel sounds *Ah* or *Oh* (see Figs. 29 and 30).

12. The Gramophone.

In the study of air waves we find many matters of great scientific interest in connection with that popular instrument the gramophone. There are two types of this instrument, one employing a needle and the other a jewelled point in the sound producing portion.

On examining a gramophone record we find it to be a disc made of a certain composition which softens with heat, and on it is a close spiral groove cut in the plate. In the needle records this groove is smooth at the bottom but irregularly indented at the side. The record is made to revolve steadily at about 90 revolutions a minute by the clockwork. The so-called sound-box consists of a flat metal box, carried on the end of a hollow arm, and this box has a circular disc, generally of mica, as the outer face. The centre of the disc is screwed to a pivoted arm, ending in a needle which rests in the groove in the

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record. As the record revolves, the needle travels in the groove, but is jerked to and fro by the irregularities on the side of the groove. This causes the lever to impart corresponding vibrations to the mica disc of the sound-box, and these create aerial waves which travel up the tube and make their exit from the horn. In the case of the Pathé gramophones the groove in the record is smooth at the sides but irregularly indented at the bottom. The sound-box lever ends in a metal point tipped with a small sapphire ball. This ball travels along the record groove and jumps or bounces over the uneven bottom like a bicycle on a rough road. These vibrations are communicated to the sound-box disc and then to the air.

The marvellous thing about the gramophone is the perfect manner in which it can reproduce complex sounds such as speech, singing, noises of animals, bells ringing, cornets and violins playing, and even hammers beating on anvils. The outline or profile of the irregularities on the side or bottom of the groove in the record is a copy of the wave form of the sound originally impressed on the master record, and this is faithfully reproduced in the aerial vibrations created as above described by the copies of the master record, which are sold to buyers.

This is perhaps the place to make reference to the history of a type of gramophone which is capable of giving a vastly louder sound or wave amplitude than the ordinary instruments. In this case the power

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required to create the aerial waves is not derived merely from the clockwork driving the record, but from a supply of compressed air furnished by an electric motor and pump. All that the rotating record does is to control the emission of this air and modulate it so as to produce aerial waves.

A sudden puff of air is capable of starting a compressional wave into existence in surrounding air. In fact, this is the underlying principle of all so-called wind musical instruments, *e.g.*, organ pipes, reeds, trumpets, cornets, flutes, etc.

Suppose, then, that a jet of compressed air is issuing from a pipe. If we can apply to the end of the pipe a valve which will control the jet of air and modulate it in accordance with the wave form of a musical sound, we shall produce the corresponding aerial waves.

Edison seems to have had the idea in 1876 that if such a valve could be controlled by the voice, then an instrument could be made which would greatly magnify it or act as an amplifier of speech.

In the late years of the nineteenth century Mr. Horace L. Short devised a valve intended to be used for this purpose, and a few years later the eminent engineer, Sir Charles Parsons, the inventor of the steam turbine which bears his name and has effected such a revolution in ship propulsion, turned his attention to the subject.

He invented a peculiar kind of valve consisting of a metal plate with very close narrow slits in it.

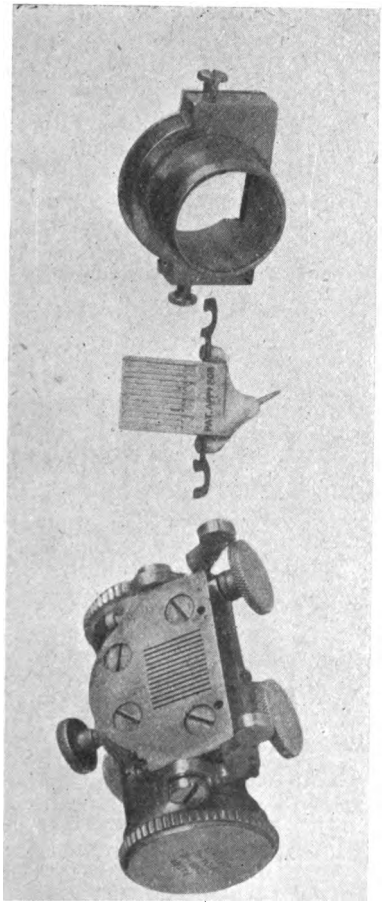
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These slits were closed by a kind of steel comb, the teeth of which overlaid the slits and closed them. If the comb was raised a little the slits became more or less open. Compressed air was supplied under the slotted plate, and its emission controlled by very slight movements of the metal comb, which last were actuated by the vibrations of some musical instrument or by a gramophone record. In this manner very powerful aerial vibrations were created by means of feebler sounds. This invention of Sir Charles Parsons was named an "Auxetophone," and it was exhibited to the Royal Society in London in 1904, and also at the Royal Institution. It was employed in 1906 to amplify the sounds of musical instruments, violins, double bass, 'cellos, etc., but its introduction was blocked or boycotted by the band-playing fraternity because they thought it would reduce the number of executants required in bands.

More recently, a similar type of instrument has been evolved by Mr. Gaydon and manufactured by Mr. Creed, of Croydon, the well-known inventor of telegraphic printing instruments. This last form of instrument has been called a "Stentorphone."

Messrs. Creed and Gaydon have now perfected a form of comb-valve which can be attached to the arm of a gramophone and actuated by any needle record. The valve is supplied with compressed air under a pressure of 10 lbs. on the square inch, furnished by a simple form of rotary pump driven

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FIG. 31.—The slotted plate and comb valve of a Creed stentorphone similar to that previously invented by Sir Charles Parsons.

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by an electric motor of ½ horse power. The indentations on the record, acting through the needle, control the motions of the comb-valve (see Fig. 31), and this, again, controls the emission of the air (see Fig. 32). The instrument therefore gives a much greater volume of sound than the ordinary gramophone, and can be heard over very large halls or for great distances in the open air. The general appearance of the instrument with its air compressor is shown in Fig. 33. The electric motor can be driven off any electric light supply circuit.

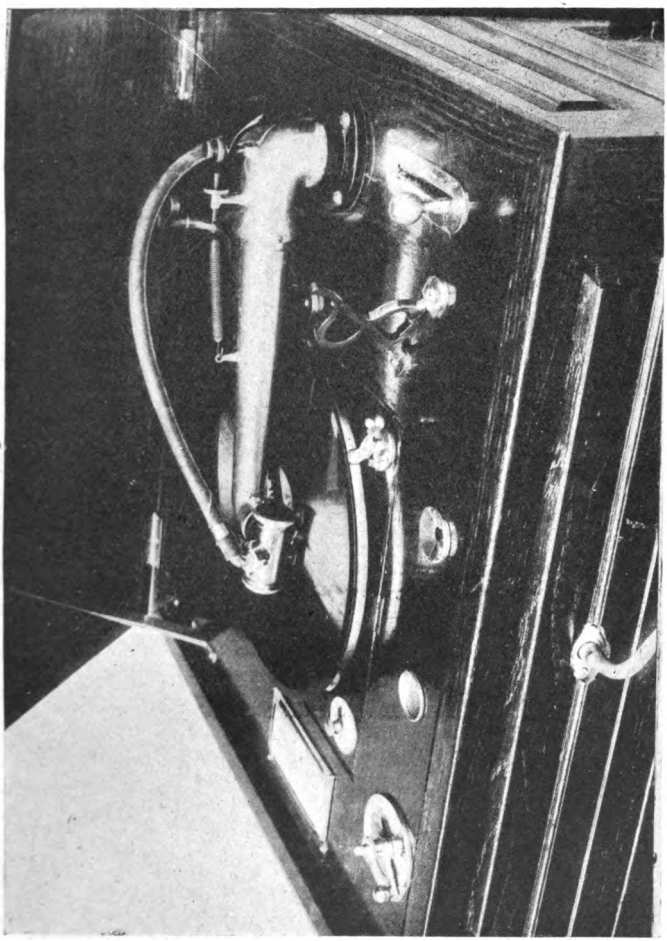
13. The Velocity of Sound Waves.

This discussion of aerial waves would probably be incomplete without some reference to methods of measuring their velocity, since these measurements have of late years received important practical applications in methods of sound-ranging for locating the position of a source of sound and in providing means for measuring the depth of the sea.

Very familiar experiences show us that a sound wave takes time to travel through the air. The delay in hearing the noise of thunder after seeing the lightning, or the explosion of a gun or rocket after seeing the flash or burst, shows that this is the case.

Modern methods of measuring extremely small intervals of time and of detecting feeble sounds have greatly increased the accuracy with which air wave velocity can be measured.

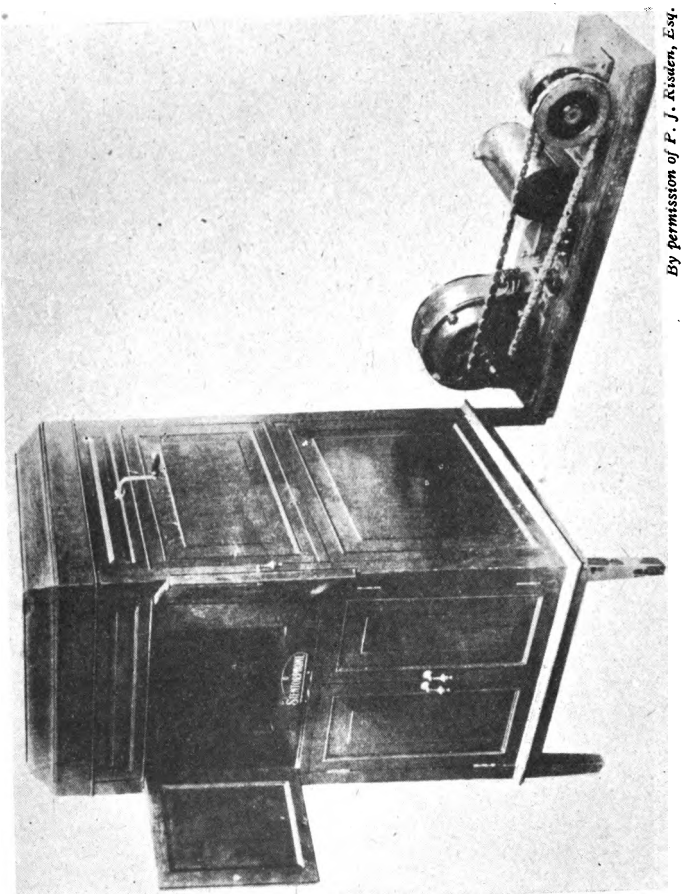
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By permission of P. J. Risden, Esq.

FIG. 32.—The tone arm, valve, air pipe delivery, and record on a Creed stentorphone.

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By permission of P. J. Kisdeu, Esq.

FIG. 33.—View of a Creed stentorphone cabinet, and of the electric motor driving the air compressor pump for supplying the compressed air.

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The following rather rough lecture experiment was devised by the writer for showing to a public audience that a sound wave takes a perceptible time to travel a distance of even a few feet.

A couple of zinc tubes, each about $2\frac{1}{2}$ ins. in diameter and 15 feet long, were united by a bend at one end so as to make a U-shaped tube, 30 ft. long. One end of this tube was covered with a diaphragm of thin sheet india-rubber, put on like the cover of a pot of jam. The other end of the tube was stopped with a cork. Two tin funnels were provided, the wide ends of which were similarly covered with india-rubber sheet, and the spouts were inserted in holes in the long tubes, one near the cork-closed end and the other near the rubber-covered end.

If a sudden tap is given to the cover of this funnel by a little metal drumstick, it starts a wave of compression which runs along the zinc tube. On the rubber cover of the funnel was fixed a little metal disc, and matters were so arranged that the act of striking the tight rubber cover of the funnel strained on it like a drumhead closed an electric circuit, as well as started an air wave travelling down the zinc tube. When that air wave reached the thin rubber cover at the far end of the tube it caused it to bulge out, and in so doing, to knock over a trigger and break or interrupt the electric circuit closed in the act of starting the wave. In this circuit was inserted an instrument called a

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milli-ampere meter, in which an indicating needle or index arm is moved through a certain angle by an electric current passing for a certain time. If, then, the air wave takes time to travel along the tube, a certain interval of time will elapse between the closing of the electric circuit by striking the funnel drum-head, and its interruption when the air wave so created reaches the far end and knocks over the trigger. From the deflection of the needle of the amperemeter, which then takes place, we can estimate the time taken for the air wave to travel 30 feet along the tube. From experiments made, it appears to be rather more than one thirty-fifth part of a second, which shows that an air wave travels at the rate of 1,100 feet per second.

Much more exact experiments of this kind have been made and described recently by Messrs. Dixon, Campbell and Parker (see *Proceedings of the Royal Society*, London: Series A, Vol. 100, October, 1921, p. 1).

They have measured with great accuracy the velocity of compressional waves in various gases at different temperatures and in tubes made of several kinds of material.

In air at 10° Centigrade they found the velocity to be 334·4 metres per second, which is equal to 1,097 ft. per second.

It has been found, however, that very loud sounds certainly travel much faster in open air than sounds of moderate intensity.

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It was pointed out as far back as 1808 by the French mathematician, Poisson, that the mathematical theory of the propagation of waves of large amplitude is entirely different from that which is valid when waves of small amplitude are considered. In 1900, M. Vieille, Engineer-in-chief of the French Ordnance Bureau, showed that the velocity of the air wave produced by bursting open a thin metal disc by an air pressure of 400 lbs. on the square inch was nearly double that of ordinary sound, whilst the air waves produced by the detonation of high explosives was nearly three times the normal.

If the velocity of an air wave is known, and if the interval of time between its arrival at two places, the distance apart of which is known can be measured, then we can locate the direction of the source of sound. For suppose *A* and *B* (see Fig. 34) to be two places, the distance *A B* being known. If a sound wave sent out from some distant source arrives simultaneously at *A* and *B*, then we know that the source of sound must be somewhere in a line perpendicular to *A B*, and passing through the point half-way between them.

If the places *A* and *B* are, say, 1,100 ft. apart, and if we are dealing with ordinary not very loud sounds, and if the air wave arrives at *A* one second before it reaches *B*, then we know the source of sound must be on the line *A B* and in the direction *B A*, produced.

If the difference in times of arrival of the sound

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at *A* and at *B* is, say, half a second, then we can find the direction in which the sound is coming as follows. Draw to scale a line *A B* (see Fig. 34) and let this represent the distance travelled over by sound in one second. Describe as *A B* a semi-circle and find a point *C* on that curve, such that *A C* is equal to half *A B*. Then join *B C* and from the centre *O* of the semi-circle draw a line *O D* perpendicular to *B C*. Then if the sound is first heard at *B* and half a second after at *A*, the sound wave is coming in the direction *D O*. If then we have another pair of similar observing stations, we can determine another line of travel of the air wave and hence from the intersection of these two lines the place of origin of the sound.

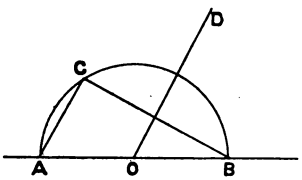


FIG. 34.

A somewhat similar method of operation called sound ranging was employed during the European War, 1914-18, for locating the position of enemy guns. Large corrections have, however, to be made for wind and other disturbing causes.

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CHAPTER III

THE ARCHITECTURE OF ATOMS

14. Molecules and Atoms.

BEFORE we can discuss the nature and properties of another type of wave called an electromagnetic wave, it will be necessary to consider briefly some of the things which modern researches have taught us concerning the structure of atoms, and the elements of which they are built up.

Twenty-five years ago no one could have given any information on this subject. In fact, even the actual existence of atoms was then in doubt. The word *atom*, derived from Greek verbal roots, signifies something which cannot be cut or divided, and any discussion on the structure of the interior of an atom would in those days have been very similar to the contents of a chapter in an old book on Natural History headed "On Snakes in Iceland," the only information given therein being, "There are no snakes in Iceland."

So with atoms the only answer to questions as to the structure of an atom would then have been, "We know nothing about their structure and probably never shall know anything."

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Although Greek philosophers twenty-five centuries ago had taught that material substances are composed of small discrete indivisible particles, no one had formulated any theory as to their inner construction, and they were only mentally pictured as extremely small spheres infinitely hard and of unknown composition. But the atomic theories of classical philosophers, such as Democritus and Lucretius, were mere speculations and had no basis in observed facts.

It was not until modern chemistry came into being by the discoveries of Cavendish, Boyle, Black, Lavoisier and Dalton, in the eighteenth and early nineteenth centuries, that valid reasons began to be given for the belief that material substance, in short, all matter is not infinitely divisible, but is composed of definite units of mass called molecules and atoms.

Suppose we consider such a substance as common table salt. We can divide it into small grains and each of these could be divided again under a microscope until we reach a particle nearly 1/100,000th of an inch in diameter, which is about the smallest size of particle visible in a good microscope. We have good reason to believe that even such a small particle would possess all the known qualities of common table salt. If we dissolve some salt in water and make a solution, no microscope yet made can show any visible particles in it, yet each drop of the liquid would taste " salt " and exhibit

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all the properties of common salt in chemical actions. Moreover, by an evaporation or boiling off of the water we can recover the salt unaltered.

Hence we have good reason to believe that when in solution the salt is divided into particles of ultra microscopic size. But chemical experiments show that this substance can yield, under the action of an agency called an electric current, the nature of which we shall consider immediately, two other substances, viz., a green poisonous gas, chlorine, and a soft metal, sodium, and therefore common table salt is called in chemical language, sodic chloride.

Moreover, effects we shall discuss later on prove that in very dilute solutions of sodic chloride and other similar salts which conduct electric currents and are decomposed by them, the constituents, which in this case are chlorine and sodium, exist partly in an uncombined state.

Hence there is a certain small mass of sodic chloride which is the least possible mass which exhibits all the properties of common salt. It is called a *molecule* of sodic chloride.

The word molecule is derived from Latin words and means a small mass or quantity. There are various substances, about 82 in all, which have never been resolved or decomposed into any other substances and these are called *elements*. The smallest possible quantity or mass of any element which can exist as such and exhibit the chemical

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properties of the substance is called an *atom* of it.

Hence the molecules of complex substances are built up of atoms held together so as to form small similar bunches or groups. In certain very simple compounds such as table salt, the molecule may consist of only two dissimilar atoms, but in organic substances, such as albumen, oils, or starch, the molecule may contain many scores or even hundreds of atoms.

Even in elementary substances such as hydrogen or oxygen in the gaseous state, the constituent molecules contain two similar atoms held together.

We have been able to determine, by methods which cannot here be described in detail, the mass or so-called weight and also approximately the size of molecules and atoms.

The view that small definite units of mass, called atoms, exist in the case of the elementary substances is strongly supported by the three laws of chemical combination, viz., Proust's Law of Definite Proportions, the Law of Relative Proportions, and Dalton's Law of Multiple Proportions. These may be illustrated as follows: Every pure chemical compound is composed of elementary substances always in the same definite and constant proportion by weight. Thus water consists of 16 parts by weight of the gas oxygen combined with 2·016 parts by weight of the gas hydrogen, which combine and produce pure water when the gases are mixed and

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an electric spark sent through them. When the analysis of a pure compound is conducted with proper care it invariably yields the same proportions of its constituent elements.

The Law of Multiple Proportion may be explained as follows :—There are two known compounds of carbon (charcoal) and oxygen gas, viz., carbon monoxide (CO), a very poisonous gas, and carbon dioxide (CO_2). In the first, the ratio of mass of carbon to oxygen is 12 to 16, and in the second it is 12 to 32. The ratio of oxygen to carbon in the second is just double that in the first. It is found that whenever there is more than one compound of two elements, the ratio by weight of these elements in the two compounds is always in a simple integer proportion.

The Law of Relative Proportion is as follows : Consider three elements, hydrogen, oxygen and carbon. The first two combine in the proportion of 1 to 8 or 2 to 16, to form water. The second and third combine in the ratio of 16 to 12 to form carbon monoxide. Finally, the first and third combine in the ratio of 2 to 12 to form a gas called olefiant gas. We see then that to each element may be affixed a certain numerical value called its *chemical equivalent*, and combinations between elements always take place in the proportion by weight of the equivalents, or in some integer multiples thereof.

These facts, and many others like them, point very significantly to the conclusion that elementary

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substances exist in small ultimate units which are of exactly the same mass and enter into all chemical reactions without change of mass.

In short, matter is atomic in structure. Atoms unite to form molecules and molecules to form visible masses, just as letters are combined to form words and words to form sentences.

The relative mass or so-called weights of each kind of atom has been measured and is called the *Atomic weight*. It is expressed in terms either of the mass of the hydrogen atom taken as equal to 1, or of the oxygen atom taken as equal to 16. The *Molecular weight* of a molecule is the sum of the masses of the constituent atoms. Two terms, viz., *a gram-molecule* and *a gram-atom* are in frequent use. These mean respectively the quantity of a chemical substance or of an element which has a mass in grams numerically equal either to the molecular or the atomic weight. Thus the atomic weight of oxygen being 16, a quantity of oxygen weighing 16 grams is called one gram-atom of oxygen. The atomic weight of sodium is 23 and of chlorine is 35·47. Hence the molecular weight of sodic chloride or table salt is 58·47, and a mass of salt weighing 58·47 grams is called one gram-molecule of sodic chloride.

According to an hypothesis first made by the chemist Avogadro in 1811, a gram-molecule of every kind of substance contains the same number of molecules.

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In the case of permanent gases taken at standard temperature 0° C. and barometric pressure 760 mm., equal volumes therefore contain the same number of molecules and a gram-molecule occupies a volume of 22,400 cubic centimetres.

Thus 2 grams of hydrogen, 32 grams of oxygen, 28 grams of nitrogen, all have a volume of 22,400 c.c. at 0° C. and 760 mm., and contain an equal number of molecules, that number being very near to 66×10^{22} or 660,000 times a million billion in English reckoning.

This means that in one cubic centimetre there are about 30 million billion molecules. In a space of one-half of a cubic millimetre, or about the volume of a small pin's head, there are ten million times more molecules of air than there are human beings alive on the surface of our earth at present. This will give some faint idea of the exceeding minuteness and number of the molecules in the air we breathe.

Non-scientific persons are apt to imagine that these figures are mere guesswork, but this is not the case. We can now count by various methods the number of molecules in a cubic inch of air with quite as close an approximation to truth as we can count the number of men, women and children in Great Britain by a census taken on the night of any given date.

15. Dimensions of Atoms.

As regards the sizes of atoms and molecules there are various lines of argument which lead to the con-

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clusion that, approximately speaking, the diameter of an atom is of the order of one hundred millionth of a centimetre. This means that if a million atoms were placed in contact like marbles arranged in a row, they would only occupy a length of 1/250th part of an inch, or less than the thickness of the thinnest sheet of tissue paper. To count this million atoms would take at least a week, counting without stopping day and night.

An approximate measurement of atomic diameters is derived from the study of thin films of various kinds.

Skilled gold beaters can beat out one ounce of gold until it covers an area of 240 square feet. The thickness of the sheet would then be about four-millionths of an inch.

There are three units of length which are convenient for measuring very small lengths or thicknesses and these are as follows :—

A millimetre (1 mm.) is the thousandth part of a metre and is about 1/25th part of an inch.

A micron (1μ) is the thousandth part of a millimetre.

An Angström unit (1 A.U.) is the ten-millionth part of a millimetre, and therefore the ten-thousandth part of a micron or 10,000 A.U. = 1μ.

Roughly speaking, the diameter of an atom is about two to five Angström units.

It is possible to prepare gold leaf the thickness of which is about one-tenth of a micron, or 1,000 A.U.

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Such leaf, when held up to the light, has a green colour, or is semi-transparent and transmits green light.

This gold leaf has, however, several hundred layers of atoms in its thickness, probably 300 to 500 atoms. We can, however, prepare thinner films of soapy water. If a soap bubble is blown with a suitable material, or better still, if a metal ring is filled with a soap film by dipping it into the soap mixture, and if this film is placed in a glass dust-free box in a vertical position, the film begins to thin away by drainage from the top part. Presently we notice certain small round black spots which look like holes, but are not holes, because in proper positions we can see an image of a bright light source, such as the sun reflected by them. It is possible to measure by several methods the thickness of the film in these black spots. It is found to be about 60 A.U., or six thousandths of a micron. This film, however, must be of a thickness equal to the diameter of several atoms.

The late Lord Rayleigh (3rd Baron) measured the thickness of still thinner films of oil floating on the surface of water and found them to be about 20 Angström units (A.U.) in thickness ($= 2 \times 10^{-7}$ cm.).

M. Devaux, by another method, produced films of oil on water of half the above thickness, viz., 10 A.U. In this last case the film is probably formed of a single layer of molecules of oil, and hence

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we see that molecular diameters must be between $1/10^7$ and $1/10^8$ of a centimetre, or approximately be of the order of one hundred millionth of a centimetre or from one to five times this last length.

At this stage we must, however, define a little more carefully what we mean by the diameter of an atom or molecule. We shall show presently that atoms are not solid, sharply defined masses like billiard balls, but in all probability resemble solar systems in miniature, in which a number of still smaller particles circulate round a nucleus like planets round the sun.

16. The Kinetic Theory of Gases.

It will be necessary, therefore, to sketch in outline the kinetic theory of gases or theory of the motion of gas molecules.

In a mass of air or gas the constituent molecules are not at rest, but flying hither and thither with immense and various speeds in every possible direction. We know that this must be the case from the facts of diffusion. If we have two vessels, one full of air or other gas and the other exhausted or vacuous, and if they are connected by a pipe in which there is a plug of porous clay or unglazed earthenware, we find that after a time some of the gas will have passed through the plug and diffused into the vacuous space. Also if the two vessels contain gases of different densities, but at the same pressure, such as hydrogen and oxygen, then they both

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diffuse in opposite directions, but the lighter gas diffuses faster than the heavier gas. In a certain time the gases will have mixed completely so that each vessel will contain the same proportion of each gas.

We know that the gas in any closed vessel exerts a pressure on the walls. This pressure is a force in a dynamical sense of the word, and is due to the bombardment of the walls by these flying molecules. Let us suppose that there are N molecules in one cubic centimetre and that each molecule has a mass m and is moving with a velocity v. This velocity is not the same for all molecules, some are moving quickly and some slowly at any instant. Of the N molecules we may suppose one-third or $N/3$ to be moving at any instant perpendicularly to one surface of the cube of 1 cm. in side and 1 square centimetre in area. If we take v to be an average velocity them mv is the average momentum of each molecule, and when it strikes the side of the cube and rebounds from it, its momentum $+ mv$ is changed in direction to $- mv$ in the time taken for the molecule to move over a distance of 2 cm. Hence the change in momentum is $2mv$ in a time $2/v$ seconds.

Force is defined as the rate of change of momentum and the time rate of change of momentum or force is in this case $\frac{2mv}{\frac{2}{v}} = mv^2$. Hence the pressure

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on the side of the cube due to the $N/3$ molecules is $\frac{1}{3} Nmv^2$.

Suppose we now take v to be, not the actual velocity of one molecule, but the *square root of the mean of the squares* of all the various molecular velocities, called the R.M.S. velocity, then since $Nm = d$ is the mass of the gas in 1 c.c., we have for the gas pressure p on a surface of 1 square centimetre the expression

$$p = \tfrac{1}{3} dv^2$$

Hence it follows that the *mean square velocity* v^2 is $3p/d$ and the root-mean-square velocity v is $\sqrt{3p/d}$, where d denotes the absolute gas density.

The pressure of a gas per square centimetre corresponding to a height of the barometer of 760 mm., or nearly 30 inches, of mercury at 0° C., is very nearly one million dynes, or absolute units of force in the metric system. The density of hydrogen gas is 1/11,200 because 11,200 c.c. of this gas weigh one gram. Hence the R.M.S. speed of the hydrogen molecule is $\sqrt{3 \times 10^6 \times 11{,}200}$ centimetres or 1,830 metres per second.

In the case of oxygen, which is 16 times denser than hydrogen, the R.M.S. speed of the molecule is close to 460 metres per second.

It is important that the reader should clearly understand what the above statements imply.

The gas molecules are flying in all possible directions and with very different speeds. If we

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could divide up the molecules into a very large number of groups of nearly equal velocity according to their speed, but without taking regard to direction of motion, we should find that a very small number of molecules had a zero or very small velocity and a very few had a considerable velocity, but the great majority approximate in speed to a certain "most probable speed," which is very nearly the same as that obtained by squaring the numerical value of the speeds of the different groups and then taking the square root of the mean of these squares, in other words, obtaining the R.M.S. speed.

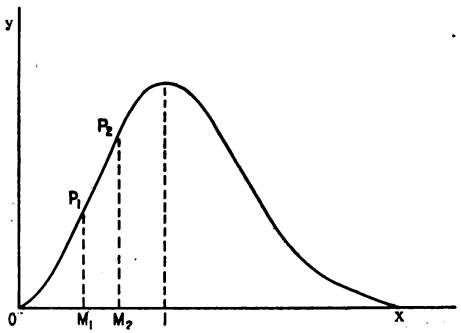


FIG. 35.—Maxwell's curve or graph of $y = x^2\epsilon^{-x^2}$.

Clerk Maxwell was the first to give a general law in the form of a mathematical expression and to give a curve for the distribution of velocity amongst gas molecules. The curve shown in Fig. 35 is a curve whose equation is

$$y = x^2\epsilon^{-x^2}$$

Where $\epsilon = 2{\cdot}71828$ . . . etc., viz., the base of the Napierian system of logarithms. The curve is so drawn that the abscissa OI of the maximum ordinate

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is taken as equal to unity. The value of y is zero both for $x = 0$ and $x =$ infinity. If we take two ordinates P_1M_1, P_2M_2, then it can be shown that the value of the area $P_1M_1M_2P_2$ multiplied by $4/\sqrt{\pi}$ gives the fraction of the number of gas molecules in any volume, the speeds of which lie between values denoted by the abscissæ OM_1 and OM_2.

Thus, for instance, in the case of oxygen gas molecules, whose R.M.S. speed is 461·2 metres per second, the following table taken from Meyer's "Kinetic Theory of Gases," gives the speeds of various groups of molecules in metres per second.

		Metres per second
13 to 14	molecules have speeds from	0 to 100
81 to 82	,, ,,	100 to 200
166 to 167	,, ,,	200 to 300
214 to 215	,, ,,	300 to 400
202 to 203	,, ,,	400 to 500
151 to 152	,, ,,	500 to 600
91 to 92	,, ,,	600 to 700
76 to 77	,, ,,	700 and above

It will thus be seen that all but about 10 per cent. of the molecules have speeds which lie between half and double the R.M.S. speed of 461 metres per second.

It will thus be evident that in a mass of oxygen gas the molecules are flying about in all directions for the most part with speeds which lie between

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500 and 2,000 miles an hour. A very few are moving more slowly and a few more quickly.

In the case of hydrogen gas which has an R.M.S. speed about four times greater than oxygen, the molecules are moving for the most part with speeds from 2,000 to 8,000 miles an hour or 100 times faster than express trains.

In the course of this extremely rapid motion the gas molecules collide with one another. The average distance they move over between two collisions is called *the mean free path.*

In the case of air at normal pressure and temperature the mean free path is about 1/250,000th part of an inch or 1/10,000th part of a millimetre, or 1/10th of a micron. This is roughly about 500 times the diameter of a gas molecule. The mean free path varies inversely as the pressure of gas. Hence, if we make a so-called vacuum by removing all but one-millionth of the air from a vessel, the mean free path is increased to about four inches in length.

We can now give a more exact definition of what is meant by the diameter of an atom or molecule. It is the least distance between the centres of two atoms or molecules at their closest approach during a collision.

If D is the diameter of the sphere of impact or atomic diameter as defined above, and if N is Avogadro's constant, or the number of molecules in a gram-molecule, and if V is the volume of this

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gram-molecule and L is the mean free path, then Clausius showed long ago that the relation between these quantities is given by the equation $\pi\sqrt{2}LND^2 = V$ where π is the circular constant 3·1415 . . . .

From this equation we can obtain, as given by J. Perrin in his book on "Atoms," translated by D. Ll. Hammick (Constable & Co., London), the diameters of various molecules, as below :—

Helium	.. .. ..	1·7 by 10^{-8} cm.
Argon	.. .. ..	2·8 ,,
Mercury	.. .. ..	2·9 ,,
Hydrogen	.. .. ..	2·1 ,,
Oxygen	.. .. ..	2·7 ,,
Nitrogen	.. .. ..	2·8 ,,
Chlorine	.. .. ..	4·1 ,,

The reader should note that the symbol 10^{-8} means one divided by 100 millions, or 1/100,000,000.

It will be seen that the diameter lies between about $1\frac{1}{2}$ and 4 Angström units, each of which is one hundred millionth of a centimetre. Since we know that Avogadro's constant is a number near to 66×10^{22}, which is the number of molecules of gas in 22,400 cubic centimetres by volume, and since we know that this volume of hydrogen weighs 2 grams and the same volume of oxygen 16 grams, it follows that we know the absolute mass or so-called weight of a molecule of these gases ; it is easy to find that the mass of an atom of hydrogen is near to $1{\cdot}63 \times 10^{-24}$ gram, where 10^{-24} means 1

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divided by a billion times a billion. In other words, a billion times a billion atoms of hydrogen weigh 1·6 grams.

We know, therefore, the mass and diameter of various kinds of gas molecule and the number of them in a cubic centimetre at standard temperature and pressure. We have to realise that the molecules of the air we breathe are little particles of matter somewhere about a hundred-millionth of an inch in diameter, flying about in various directions with the velocity of a rifle bullet, or say, 1,500 feet or so per second, striking against other molecules about 5,000 million times in a second, moving on an average about four-millionths of an inch between each collision, and so numerous that about 400 million billion are contained in every cubic inch of space.*

The pressure which the air exerts on the sides of a vessel containing it, which at ordinary barometric weight is about $14\frac{1}{2}$ lbs. on the square inch, is due to the incessant bombardment of the inner surface of the containing vessel by these small but numerous projectiles.

Since the mass of an atom of hydrogen is $1{\cdot}6 \times 10^{-24}$ gram and the diameter of a molecule (two atoms) of hydrogen is $2{\cdot}1 \times 10^{-8}$ cm., it follows that the mean density of a hydrogen atom is about

* In English reckoning a billion means a million times a million, or 1 followed by twelve cyphers, but in the United States a billion means a thousand times a million, or 1 followed by nine cyphers.

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3·3 times that of water, and that of an oxygen atom about 51 times.

17. Atomic Structure.

We are then naturally led to consider the very important question of atomic structure and architecture to which all the foregoing discussion has been only preliminary.

The first step in this knowledge was taken about 1898 or 1899, when Sir Joseph Thomson began his epoch-making work which led to the discovery of the *corpuscle* or *negative electron* as a constituent element of all atoms. This work grew, very naturally, out of the previous researches of Sir William Crookes on electric discharge in high vacua, and the discovery in 1895 by W. Röntgen of the so-called X-rays, which marked the beginning of a new era in physics.

Crookes had found that when a glass bulb exhausted to a very high vacuum had one platinum electrode, called the cathode, sealed through the glass connected to the negative terminal of an induction coil, and another similar electrode, called the anode, connected to the positive terminal of the coil, then when the induction coil was in action, not only was the glass rendered fluorescent, but particles of some kind were projected from the cathode, which moved away in straight lines, normal to the surface of the cathode, could produce fluorescence in many substances placed in their

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path, could cause little mica vanes to rotate like a windmill, and also could cast shadows of metal objects on the glass wall of the tube (see Fig. 36). Crookes showed that these particles each carried a charge of negative electricity.

Crookes named these particles "radiant matter," but they were subsequently called "cathode rays" or "cathode ray particles." Up until 1895, this high vacuum electric discharge hardly possessed more than a purely scientific interest, but in that year W. Röntgen made a discovery of great practical importance. He found that when such a high vacuum tube was in operation and the glass fluorescent, paper or wood coated with a fluorescent material such as barium platinocyanide, was also made fluorescent, even outside the vacuum tube, when held near it, and, moreover, that some substances, such as heavy metals, stopped the radiation producing fluorescence, whereas this radiation passed freely through wood, paper, leather and other materials opaque to light rays.

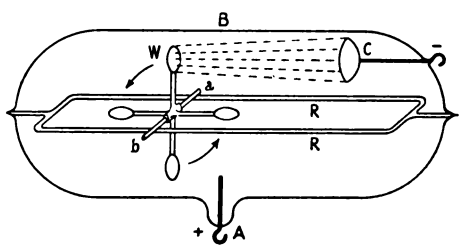


FIG. 36.—Crookes' electron mill. B. Highly exhausted bulb. C. Cathode or negative cathode. A. Anode or positive electrode. W. Little Rotor with mica waves which rotates and rolls along glass rails R, R under impulses of electrons radiated from cathode.

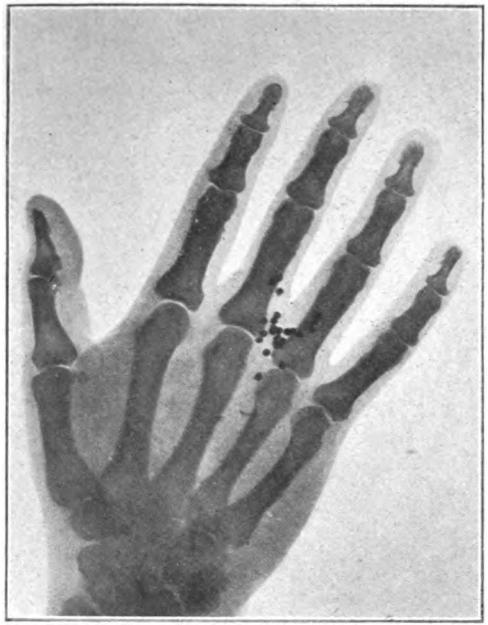
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The great sensation of that day was, however, the discovery that the new rays, then called X-rays, from their unknown nature, passed freely through the fleshy tissues of the living human hand, but were more or less stopped by the bones. Also that since these rays could affect a photographic plate enclosed in a black paper envelope, it was possible to photograph the bones in the living hand and unerringly fix the position of any metallic bodies, e.g., bullets, needles, etc., in the flesh (Fig. 37). Again, it was found that these X-rays produced a certain degree of temporary electric conductivity in air or other gases through which they passed.

The investigation of the nature of the cathode rays and of the X-rays was taken up very carefully about the end of last century. Two views had previously been held as to the cathode rays. Crookes and his followers maintained that they were material particles of some kind projected from the negative electrode in the high vacuum tube. Other physicists regarded them as some form of ætherial vibration.

Sir Joseph Thomson settled the question by experiments of a remarkably ingenious and important character. If an electrified particle is made to move across the space between the poles of a powerful magnet in a direction at right angles to the line adjoining these poles, it experiences a deflecting force which is at right angles to the direction of its motion and that of the so-called magnetic force

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X-ray photograph of a hand with shot embedded in it.



X-ray photograph of finger with a needle embedded in it.

FIG. 37.

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which last lies in the direction of the line joining the magnetic poles. This magnetic force is a quantity measurable in certain units. Let us denote by the letter H the magnitude of this magnetic force. Let the velocity of the electrified particle be v centimetres per second, and let it carry an electric charge, denoted by the letter e, as regards amount. Then when the particle carrying an electric charge of e units moves with a velocity v in a direction at right angles to a magnetic force H, it experiences a deflecting force numerically equal to the product. Hev, which is in a direction at right angles to the direction of H and v.

Under these conditions the electrified particle of mass m is being continually acted on by a force at right angles to its direction of motion and hence it moves in a circle of radius v, such that $Hev = mv^2/r$.

Therefore we have the relation

$$\frac{m}{e} v = Hr.$$

Suppose in the next place that we cause an external electric force to act on the electrified particle having an electric charge e. Let the magnitude of this electric force be denoted by E. Then a force measured by the product Ee acts on the particle. Let the direction of the impressed electric force E be so adjusted that the deflecting force produced by it on the electrified particle is exactly opposite in direction and equal in amount to the deflection produced by the magnetic force. We can

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then equate the two expressions for the deflecting force acting on the particle and have the equation

$$Hev = Ee$$

or

$$v = \frac{E}{H}.$$

Hence, if we measure, as we can do, the magnetic force and the electric force, we can determine from their numerical ratio the velocity v of the cathode particle.

Again, having found the velocity v we can from the previous equation, viz., $Hev = mv^2/r$ or $Hev = mv$, find the ratio of e/m or of electric charge to mass of the cathode particle. For from the above equations we see that

$$\frac{e}{m} = \frac{E}{H^2 r}.$$

Hence, if we measure the radius of the circular path of the cathode particle when deflected by the magnetic force H, and also the electric force E, at right angles to H, which is necessary just to annul the deflection, we can calculate the value of E/H^2r and thus determine the ratio e/m. This ratio is an extremely important number and the investigations for its exact determination have been very numerous. The apparatus generally used is shown in Fig. 38. It consists of a glass tube about two inches wide, ending in a large bulb B, 10 or 12 inches in diameter. At the extreme end is sealed in a platinum wire, ending in an aluminium dish C, which forms the

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cathode or negative electrode. The positive electrode *A* is another wire sealed into a short side tube. When these electrodes are connected to the secondary circuit of an induction coil, or better still to the poles of an electrostatic generator such as a Wimshurst electrical machine, which keeps the cathode negatively electrified, a torrent of cathode particles are projected from it, when the tube is highly exhausted of its air so as to make a good vacuum in it.

In the vacuum tube are placed a pair of baffle plates, *E*, with small holes in them, which allows a thin stream of cathode particles to pass. These fall on the spherical end of the tube, which is coated inside with a phosphorescent material called willemite, or with powdered zinc blende. The cathode particles impinging on this screen make a bright green spot of light on it. Within the tube are also placed a pair of metal plates, *pq*, which can be electrified, one positively and the other negatively, so as to create the required deflecting electric force we have denoted by *E*. Also that same part of the tube is placed between the poles of a powerful magnet so as to supply a deflecting force *Hev* in

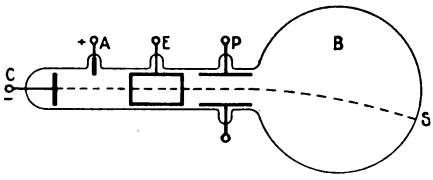


FIG. 38. — Cathode ray tube and bulb. *C*. Cathode or negative electrode. *B*. Highly exhausted bulb with fluorescent screen on its spherical end *S*. *A*. Anode. *E*. Baffle plates. *P*. Deflecting plates.

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the contrary direction, but in the same line as the electric force E.

From the deflection caused by the magnetic force alone we can find the radius r of the curve along which the cathode particle moves, and we can thus determine both the velocity v and the ratio e/m.

When these experiments are carefully conducted, it is found that the velocity of the cathode particle will vary with the potential difference, as it is called, of the electrodes, but in a high vacuum tube may be of the order of 100 million feet per second, or about one-tenth of the velocity of light. This is an enormous speed, and it is due to this immense velocity that the cathode particles are able to make a luminous spot on the phosphorescent screen.

Sir Joseph Thomson found, in 1899, that the ratio of e/m for the cathode particle was quite independent of the metal of which the cathode was made or of the residual gas in the tube. Under all circumstances exactly the same ratio was obtained. The numerical value was nearly $1{\cdot}77 \times 10^7$ when the charge e was measured in the so-called electromagnetic units. This electromagnetic unit of quantity is the quantity of electricity conveyed by a current of 10 amperes when flowing for one second or one ampere when flowing for 10 seconds, or about the quantity of electricity which passes through the filament of a 16 candle-power 200-volt lamp in a minute and a half.

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This constancy in the ratio of e/m for all particles indicates that they are identically the same in every case.

We must make a little digression to explain the manner in which this ratio can be determined for the hydrogen atom and what conclusions can be drawn from it.

If we place two platinum or gold plates in water which is slightly acidulated and connect these plates with a storage battery of a couple of cells, we see bubbles of gas arising from both plates. By collecting these gases in separate tubes we can prove that the gas arising from the plate in connection with the positive pole (marked red) of the storage cell is oxygen and the gas collected at the other plate is hydrogen. By measuring the volume of these gases collected we can find that the passage of a current of one ampere for one second through the acidulated water liberates 1·04 ten-thousandths of a gram of hydrogen in the form of gas. These two gases are produced by the electro-chemical decomposition of the acid which is mixed with the water. Suppose for the sake of simplicity that we consider the water to have been acidulated with hydrochloric acid. Each molecule of this acid consists of an atom of hydrogen united to an atom of chlorine, and the chemical formula is therefore *HCl*.

Absolutely pure water is not a conductor of electric current, or at least a very bad one.

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If we put into this water a little hydrochloric acid the water causes a number of the hydrochloric acid (*HCl*) molecules to become separated into atoms of hydrogen which are positively electrified and atoms of chlorine which are negatively charged. In this state the electrified atoms are called *ions* and the acid is said to be partly *ionised*. The word *ion* means a wanderer, and they are so called because they wander about in the liquid. When a hydrogen ion collides with a chlorine ion they may become reunited into a hydrochloric acid molecule for a short time, but presently the ions are detached again. If then we place in the acid water two metal plates which are electrified the negative plate attracts and draws to it at the instant when it is free the positively charged hydrogen ion, and the positive plate similarly attracts the chlorine ions.

The chlorine ions, however, have a strong affinity for hydrogen ions, and they even take these away from molecules of water, thus re-forming *HCl* and liberating oxygen ions against the positive plate. These hydrogen ions than take negative electricity from the negative plate, and the oxygen takes positive electricity from the other plate, re-forming hydrogen and oxygen atoms which in turn unite, pair and pair, to form molecules, and these constitute the bubbles of gas liberated.

We see, therefore, that the electric current which passes through the electro-chemical vessel consists

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of charges of electricity which are carried by hydrogen and chlorine ions. To every hydrogen atom there corresponds a certain electric charge. If, therefore, we wish to determine the ratio of charge to mass for a single hydrogen atom or ion we have only to determine how much electricity passes, corresponding to the liberation of one gram of hydrogen at the negative electrode. Now, exact experiment shows that a current of one ampere flowing for one second conveys a quantity of electricity called one coulomb, which is one-tenth of an absolute unit of electric quantity, and this liberates 0·0000109 grams of hydrogen. Hence, the ratio of charge to mass or e/m for the hydrogen ion is a number near to 10,000 or 10^4. We have seen, however, that the ratio of charge to mass or e/m for the cathode particle is $1{\cdot}77 \times 10^7$ or $1{,}770 \times 10^4$ or 1,700 to 1,800 times greater than e/m for the hydrogen ion.

The question then at once arose : is this difference due to a difference in charge or to a difference in mass between the cathode particle and the hydrogen atom or ion ?

18. Cathode Particles or Electrons.

Sir Joseph Thomson gave a reply to this question in 1899 by experiments of extraordinary skill and ingenuity.

It was found that particles in every way similar to cathode particles are liberated from the surface

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of polished zinc and some other metals when they are illuminated by ultra-violet light or light rays of very short wavelength. Also they are liberated from Radium, and the X-rays of Röntgen liberate them from molecules of air.

When produced by either of these methods these cathode particles have the power of condensing round themselves water vapour present in air and forming a minute water spherule or drop of water.

The white clouds we see floating in the sky are composed of such small water drops. All air, unless specially dried, has in it a certain proportion of water vapour which is an invisible gas. If, however, the air is cooled below a certain point, it cannot hold as much water vapour in solution, and it gets rid of and deposits the excess by forming a cloud or mist; this is the explanation of the early morning mists in the atmosphere, which are really formed during the night, when the atmosphere is cooled and the excess of water vapour condensed to water spherules. These small drops of water fall very slowly through the air owing to the friction or viscosity of the air.

Many years ago Sir George Stokes gave a formula connecting together the diameter (d) of the drop with viscosity (q) of the air and the final or constant velocity (v) which the falling drop attains. This formula is $v = \frac{1}{18} \frac{gd^2}{q}$, where g stands for the

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acceleration of gravity and is nearly 981 in centimetres and seconds as units.

When moist air is chilled by being suddenly expanded it has been found that the excess of moisture is not readily converted into droplets or mist unless there are dust particles in the air. These, however, assist the condensation by affording nuclei round which the water vapour condenses. Many years ago it was discovered by Mr. C. T. R. Wilson that cathode particles could act in the same manner in perfectly pure dust-free air.

If such pure air is suddenly expanded and cooled a cloud does not form, but the air becomes supersaturated with moisture. If then cathode particles are introduced a cloud forms at once. Wilson found that if the supersaturation did not exceed a certain amount only the negative or cathode particle acted as a nucleus or core for the condensation of water vapour round it, and a cloud or mist is formed in the vessel in which the moist air is suddenly expanded.

Sir Joseph Thomson and Prof. H. A. Wilson applied this method to determine the cathode particle electric charge as follows :

They suddenly expanded pure dust-free air in a glass vessel and thus supersaturated the air with moisture. They then introduced into this air a number of cathode particles either by allowing ultra-violet light to fall on a zinc plate in the vessel or else by exposing the air to the X-rays. The

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expansion was performed in a glass vessel having in it two metal plates, an upper and a lower, which could be connected at pleasure to a voltage battery of a certain number of cells so as to make the upper plate positive and produce a certain electric force in the space between the plates. When the cloud was formed by the condensing action of the cathode particles each of the latter condensed round itself a drop of water and began to fall downwards. The rate of falling, by Stokes' law, is determined by the size of the drop, and from the observed rate of sinking of the upper sharp surface of the cloud we can calculate the diameter of the minute drop of water from the formula given above and hence the mass of the drop. When the cloud has sunk a certain distance the upper metal plate is given a positive electric charge, and this produces an electric force E in the space between the plates which can be adjusted until it just arrests the fall of the drops.

We then know that since each drop contains a cathode particle of electric charge e we must have the equation

$$Mg = Ee$$

where M is the mass of the drop and g the acceleration of gravity. From this equation e can be determined.

Some admirable measurements of the same kind, only using oil or mercury vapour in place of water vapour, have been carried out by Professor R. A. Millikan in America. The best and final result is

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that the cathode particle carries a negative electric charge of $4{\cdot}774 \times 10^{-10}$ electrostatic units or $1{\cdot}591 \times 10^{-20}$ electromagnetic units. In other words, six million billion cathode particles carry between them a quantity of electricity equal to that conveyed by a current of one ampere in one second.

It was thus found that this very small quantity of negative electricity is a natural unit which cannot be divided, and is in short an *atom of electricity*. Electricity was thus seen to be a commodity like cigars or cigarettes or things of the kind that are supplied only in multiples of some finite unit.

To this atom of negative electricity the late Dr. Johnstone Stoney gave the name of *the electron*, but the term electron is now applied to the cathode particle, or negative corpuscle as a whole.

It became clear, therefore, that identical electrons were constituents of all material atoms and could be extricated from them.

19. Electrons as Constituents of all Atoms.

It was not then a long step from this point to the suggestion that atoms consisted of groups of electrons, arranged in a certain way and held together by the attraction of some form of charge of positive electricity. The first suggestion was that this positive charge of electricity, the nature of which was unknown, existed in the form of a

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sphere of the size of the atom and that the negative electrons were distributed through it like pips in an orange, but able to circulate about or revolve in it.

The late Lord Kelvin made this suggestion first, and its consequences were mathematically developed by Sir J. J. Thomson.

If we suppose the sphere of positive electricity to be composed of stuff which attracts electrons external to itself with a force which is inversely proportional to the square of the distance, then it can be shown that a sphere of such positive electricity would attract an electron embedded in it towards its centre, with a force proportional to the distance of the electron from the centre. If then by any means the electron is set in motion, it will revolve round the centre of the sphere of positive electricity in a circular orbit included within the boundary of that positive sphere.

If a number of such electrons are included in the sphere they will arrange themselves in certain rings or orbits, certain arrangements being stable and others unstable. An illustration of this sort of structure is found in an interesting experiment due to Mayer.

A large number of sewing needles are thrust through little discs of cork. The needles are all magnetised, and then, if placed in water in a basin with the cork button slid along to one end, the needles will all float vertically in the water. If then the upper ends are all similar magnetic poles, the

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needles will repel each other like electrons, and if left to themselves will get as far apart as possible.

If the opposite pole of a bar magnet is now held near the surface of the water, the needles will be drawn to it but will be mutually repelled. Under this double action they will arrange themselves in certain forms (see Fig. 39). Thus three needles will set themselves at the angular points of an equilateral

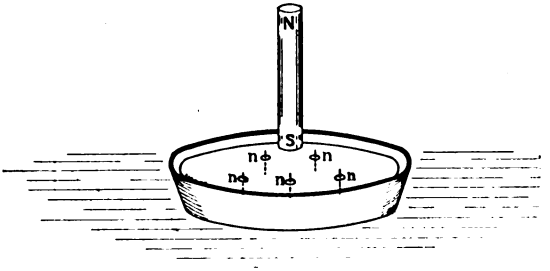


FIG. 39.—Mayer's magnetic experiment. Little magnetised needles floating vertically in water and caused to arrange themselves in a pattern by a magnet *NS* held over them.

triangle, four at the corners of a square, five at corners of a pentagon. Certain arrangements are, however, unstable, especially if the needles or electrons are in rotation round the centre, and when more than a certain number of needles or electrons exist in the group the arrangement is not stable unless they are arranged in two or more rings.

Certain facts discovered by Sir Ernest Rutherford and strongly supported by the theoretical investigations of Professor N. Bohr, of Copenhagen, seem to militate against the view that the positive electric

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charge is diffused over a sphere the size of the atom, but strongly support the view that it is concentrated in a small centre or nucleus which is very small compared with the size of the material atom itself, and perhaps not large even compared with the size of a negative electron.

The theory of atomic structure now somewhat widely held, called the Rutherford-Bohr theory, is that a chemical atom consists of a nucleus which is composed of negative electrons, held together by still smaller positive electrons, the positive electrons predominating in number so that the whole nucleus has a resultant charge of positive electricity if we assume that the charges of positive and negative electrons taken singly are equal.

Thus, for instance, the nucleus of the Helium atom is supposed to contain four positive electrons and two negative, which are bound by mutual attraction and repulsion into a compact mass, which Rutherford concludes has a diameter of not more than one ten-thousandth part of that of the whole atom, which we have seen to be of the order of one-hundred-millionth of a centimetre. This nucleus has, therefore, a resultant positive charge equal to two units, taking the unit to be the electron charge. Around this nucleus circulate two negative electrons like planets round the sun, and the atom, taken as a whole, is therefore electrically neutral.

The atom, on this theory, is a solar system in miniature. The nucleus corresponds to the central

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sun and the negative electrons to the planets circulating round it. The electrons need not revolve in the same plane nor even all in the same directions, and each orbit may have not only one planet but two, three, or more, even up to eight, as the case may be.

It will be seen, therefore, that an atom forming what we usually call solid matter is in fact a very open or porous structure, consisting of a certain number of very dense and extremely small particles distributed throughout a certain space, otherwise unoccupied, which we call the volume of the atom.

20. A Model of an Atom.

Thus if we desired to make a model, say, of a helium atom, we might place a sphere, say, the size of a football, at a certain position to represent the positively charged nucleus. Then at distances of about $1\frac{1}{4}$ miles we should have to locate two golf balls to represent the two negative electrons and to assume that these were revolving round the football like planets round the sun, but not necessarily in the same plane nor in the same direction as regards rotation.

In the case of an atom of hydrogen, the nucleus consists of a single positive electron and a single negative electron, the two revolving round their common centre of mass. When two atoms of hydrogen unite to form a molecule, we have two positive electrons at a certain distance apart, and two negative electrons revolving in a circle, the plane of

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which is perpendicular to the line joining the two positive electrons and its centre on that line.

The two negative electrons are at opposite ends of a diameter of the circle in which they revolve (see Fig. 40).

It appears from certain considerations that the diameter of this circle may be different in different molecules of hydrogen, so that these molecules are not in all cases of exactly the same volume.

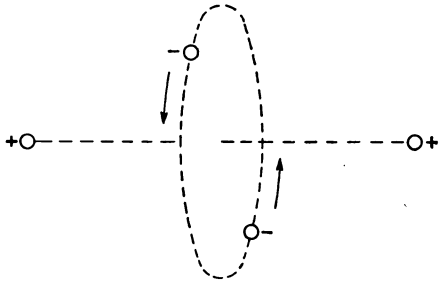


FIG. 40.—Model of a hydrogen molecule.

We have seen that the mass of the negative electron is only about 1/1,700th of the mass of the positive electron, and this leads to the conclusion that the true mass or gravitative mass of the atom resides almost entirely in the positive electrons. The reason for this may be in the much greater density and smaller size of the positive electron.

In addition to this Rutherford-Bohr theory of the structure of the atom, another view has been advanced and supported by Langmuir, which

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regards the negative electrons assembled round the nucleus as stationary and not in revolution. We shall not enter into the discussion of this theory because it entails much greater mathematical difficulties than the Rutherford-Bohr theory, in that we have to account for the fact that there must then be localities round the nucleus to which the forces acting on the negative electrons converge in all directions so as to produce stability.

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CHAPTER IV.

ELECTROMAGNETIC FIELDS, FORCES AND RADIATION

21. Lines of Electric and Magnetic Force.

BEFORE dealing at greater length with the problem of atomic structure, it will be necessary to enter into certain elementary expositions of the nature of electromagnetic fields and forces and of electromagnetic or so-called electric waves.

Theory shows that when an electrified sphere or electrically charged body is set in motion in any direction it not only exerts a force on other electrified bodies near it, called electric force, but also, when moving, acts on magnets or exerts a magnetic force along certain directions. In the case of a small charged sphere in uniform linear motion, the lines of electric force are radial, and the lines of magnetic force are circles whose centres lie on the line of motion and planes are perpendicular to it. The regions near electrified bodies or magnets are called *electric* or *magnetic fields*, and in these fields forces of attraction or repulsion are exerted on other electrified bodies or magnets which are called electric and magnetic forces respectively. These forces are exerted along certain straight or

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curved lines called lines of electric or magnetic force. Faraday considered that these lines of force are not merely ideal lines like lines of latitude and longitude, but that they have some actual physical existence and are regions in which some special actions in a universally diffused medium called æther are taking place.

Hence we may say that an electric or magnetic field has a certain discreteness or atomic structure, and that the space within a small tubular region surrounding a line of force is in some way different from the space outside.

In the case of an electrified sphere the lines of electric force radiate from the sphere as from its centre, being equally distributed in all directions, provided the sphere is at rest. Faraday showed by numerous experiments that it is impossible to create a charge of electricity of one kind without creating also an equal quantity of the opposite kind. Hence we must consider that a line of electric force must be either an endless line or, if not, must have its ends terminated by charges of electricity of opposite sign, say, by ending on positive and negative electrons respectively, or else must start from an electron and be extended to an infinite distance.

There is, however, an interconnection between lines of electric and lines of magnetic force which may be explained as follows :—

If a line of electric force is moved parallel to

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itself or in a direction at right angles to its own direction it creates a line of magnetic force which runs in a direction at right angles to that of the line of electric force and to that of the motion of the latter.

The relation of the directions may be memorised

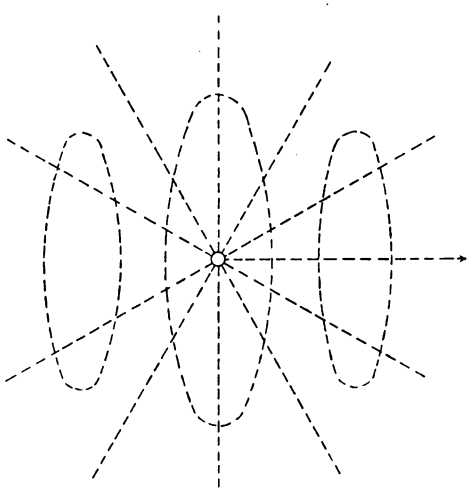


FIG. 41.—Lines of electric and magnetic force round an electron.

by means of a "hand rule," as follows: Hold the thumb, forefinger and middle finger of the *right* hand in positions mutually at right angles like three co-ordinate axes. Then let the direction of the forefinger denote the direction of a line of electric force, and that of the thumb the direction of the motion of this line at right angles to its own direction. Then the direction in which the middle

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finger points will be the direction of the magnetic force produced by its motion. It should be remembered that by usual conventions the direction of an electric line of force is the direction in which it would cause a free positive electron or positively charged particle placed on it to move. Hence for a negative electron the lines of electric force are directed *towards* the electron.

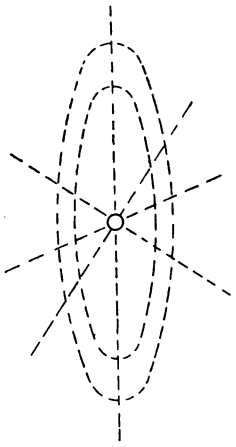


FIG. 42.—Lines of electric and magnetic force around an electron moving with high velocity.

If then we consider an electron carrying its system of radial lines of electric force to be *in motion*, we see that the result is to surround the electron with a family of circular lines of magnetic force which all have their centres on the line of motion and all have their planes perpendicular to it (see Fig. 41).

The magnetic force at any point is proportional to the velocity and also to the resolved part or component of the electric force which is at that point perpendicular to the direction of motion. It can be shown mathematically that when the velocity or speed of the electron approaches that of light, viz., 300,000 kilometres per second, the radiating lines of electric force all crowd up into the equatorial plane, which is a plane through the

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centre of the electron and perpendicular to its direction of motion (see Fig. 42).

The radial lines of electric force and embracing circular lines of magnetic force then form a sort of spider's web pattern in that equatorial plane. This is called the electromagnetic field of force of the electron. This electromagnetic field represents a store of energy. If a substance of mass m, whether a bullet or a railway train, be in motion with a velocity v, it has energy called kinetic or motional energy associated with it, which is in amount equal to $\frac{1}{2}mv^2$ or to half the mass multiplied by the square of the speed. It can be proved, though the proof is somewhat difficult, that when an electrified sphere moves with velocity v it has energy associated with it measured by

$$\tfrac{1}{2}\left(m + \frac{4}{3}\frac{e^2}{d}\right)v^2$$

where e is the electric charge, which in the case of an electron is $1{\cdot}6 \times 10^{-20}$ electromagnetic units, or $16/10^{20}$ coulombs, and d is the diameter of the sphere or electron. The letter m signifies the ordinary mass, and $4e^2/3d$ is called the electrical mass.

22. Size and Mass of an Electron.

The question has been much discussed whether the electron has any mass other than the electrical mass, and certain experiments by Kaufmann

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strongly indicate that it has not. If this is the case then the whole mass m of the electron is represented by the value of $4e^2/3d$ and the diameter d is equal to $\frac{4}{3}\frac{e}{m}e$. But now we have seen that the ratio of charge to mass or e/m for an electron is nearly $1{\cdot}774 \times 10^7$ electromagnetic units and that the electric charge e is $1{\cdot}6 \times 10^{-20}$ electromagnetic units. Hence the diameter of an electron is $\frac{4}{3} \times 1{\cdot}744 \times 1{\cdot}6 \times 10^{-13}$ of a centimetre or $0{\cdot}38 \times 10^{-12}$ cm., that is about one-third of a billionth of a centimetre. A million times a million electrons, put in a close row, would only extend a distance of about one-sixth of an inch. A negative electron is therefore very small compared with an atom, about one hundred thousandth part of the diameter of an atom. Small, however, as is the negative electron, the positive electron is probably still smaller. We have seen that in a hydrogen atom, consisting probably of a single positive and single negative electron, the negative electron contributes only 1/1,700th part of the mass. This implies that if the charge of the positive electron is the same as that of the negative the diameter of the former is only 1/1,700th part of that of the latter. We see, therefore, that the negative electron has a diameter of only about a hundred thousandth part of that of the whole atom and that the positive electron is perhaps 2,000 times smaller. We are

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now able to make a pretty clear mental picture of what an atom of matter is like according to the above theory. Imagine a cricket ball suspended in the air. At a distance of 100 or 200 feet or so from it let there be a few dozen grains of dust each not more than 1/100 inch in diameter. Let these grains, representing electrons, revolve round the cricket ball, representing the nucleus in circular orbits, the grains being arranged in shells or groups of 2, 3, 4 to 8, in various orbits, up to, say, 100 feet radius. This would suggest what an atom would look like if it could be magnified a billion times and be then viewed from a distance of several hundred yards.

23. Electromagnetic Waves.

Before considering the problems of atomic structure at any greater length it may be well at this stage to outline our present views on the nature of an electric or electromagnetic wave. We have seen that from an electron we consider lines of electric force to radiate. These lines may for the sake of brevity be called *electrolines*, and we may therefore picture to ourselves an electron as something like a golf ball in which have been stuck very long straight wires radiating equally in all directions, which wires represent the electrolines (see Figs. 43 and 44). These electrolines possess an elasticity of a certain kind. They resist stretching and endeavour to make themselves as short as possible. In fact the

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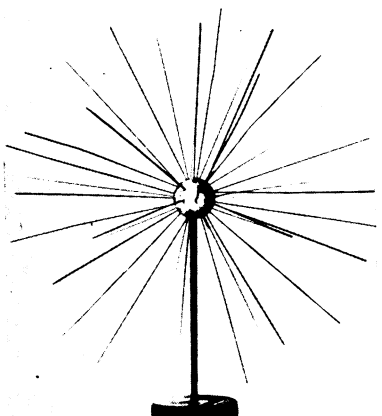
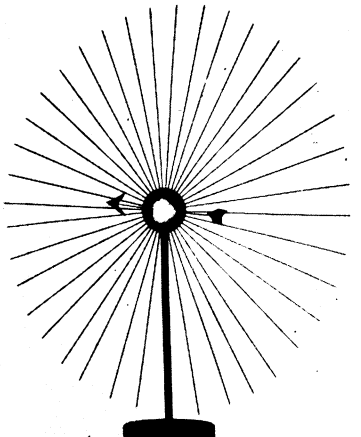


FIG. 43.—A golf ball with radial wires in it to represent an electron with its electrolines.



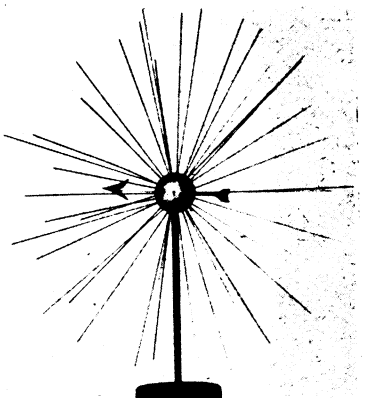


FIG. 44.—A golf ball with radial wires in it to represent an electron in motion. The electrolines crowd up into the equatorial plane when the electron is in rapid motion.

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attraction between positive and negative electrons may be regarded as the result of the endeavour of these lines to shrink up in the direction of their length. Also these lines possess a quality equivalent to mass or inertia, and the so-called electric mass of the electron to which we have already referred is

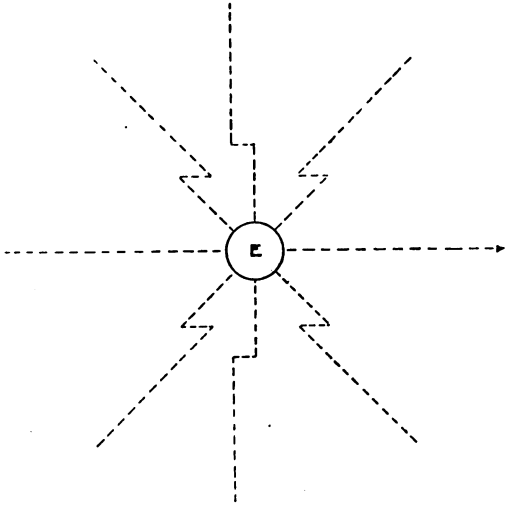


FIG. 45.—Kinks produced on radial electrolines of an electron *E* when the latter suddenly jumps forward. The dotted lines denote the electrolines.

merely the mass of the entirety of these electrolines and of the magnetolines produced by their motion.

Suppose then that an electron at rest is caused to make a sudden jump forward. It carries with it the ends of the electrolines which terminate on it, but the inertia of the line causes the rest of the line to be

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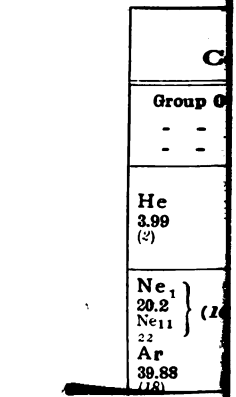
left behind for a moment, and the result is the production of a *kink* or dislocation in the lines (see Fig. 45). This kink, however, travels outwards along the lines as the whole electroline picks up the motion. We have, however, seen that the lateral or sideway motion of an electroline gives rise to a magnetic force at right angles to itself and to the direction of its motion. Hence, as the "kink" in the electroline travels outwards it is accompanied by lines of magnetic force or magnetolines created by the motion of the electrolines.

These two sets of lines are at right angles to each other and to the direction of motion. Experiment shows that this kink travels outwards with a velocity of 300,000 kilometres per second in empty space or with the velocity of light in any medium in which the electron is placed.

This movement of electric and magnetic lines of force lying in the same plane, this motion being in a direction at right angles to the plane of the two sets of lines, is called an *electromagnetic pulse* or solitary wave and is also called *electric radiation.*

The same kind of electric radiation will be produced if an electron in uniform motion is suddenly stopped or has its velocity changed or suffers acceleration. There are, however, two kinds of acceleration. Velocity may be changed in amount, but not in direction, as when a stone is falling towards the earth, or the velocity may be continually changed in direction, but not in magnitude, as when

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a mass revolves with uniform speed in a circle. It appears, for reasons too long to give at this point, that an electron when revolving with constant speed in certain paths round a nucleus, although in one sense of the term experiencing an acceleration towards the nucleus, is yet not radiating electromagnetic waves and therefore not losing energy. On the other hand, if an electron jumps backwards and forwards in a straight line it does radiate, although the direction of its motion is always in one line. If then we imagine a number of electrons to be placed in a row in one line and all to jump to and fro in that line through a small range simultaneously the whole lot of them would radiate and would produce an electromagnetic wave, the wave surface of which would be a co-axial cylindrical sheath or surface to the line of electrons. We shall see, when we come to discuss the subject of wireless telephony, that this is just what happens in the case of the aerial of a wireless telephone transmitter.

Before proceeding further with the consideration of the problem of electric radiation by the atoms and electrons, it will be necessary to return to the discussion of a few more matters connected with the architecture of atoms.

24. The Periodic Law of Atomic Properties.

It was long ago pointed out by the English chemist Newlands, and the Russian chemist Mendelejeff, and by Lothar Meyer, that if the names of

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the elements are written down in the order of their atomic weights, the same kind of properties repeat themselves at regular intervals in the series.

It is now usual to arrange the elements in a table called the Periodic Series, which brings out these points clearly.

If we rule up a sheet of paper into nine columns and twelve rows, we can write in each of these spaces, or in nearly all of them, the names of the elements in order of their atomic weights, proceeding from left to right in each row and downwards in each column. We then find that when arranged as shown in the table (p. 120) all the elements of similar character fall into the same column or group.

The atomic weight of hydrogen is 1·008, when that of oxygen is taken as equal to 16.

The columns are numbered 0 to 8. In column 0 we find all the elements like helium, argon, neon, etc., which are non-valent and do not form any chemical compounds. In column 1 we have the mono-valent highly electro-positive alkaline metals like lithium, sodium, potassium, etc., in column 7 the haloid elements, like fluorine, chlorine, bromine, iodine, and in column 8 certain groups of three metals.

At the end of the series we come to the radio-active elements, radium, thorium and uranium, this last being the heaviest atom, with an atomic weight of 238·2.

We can also attach to each element a number

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called its *Atomic Number*, given in italics in brackets in the table, which represents its numerical order of the elements in the series. The atomic number of hydrogen is 1 and that of uranium 92.

It is seen that at the beginning of the series the atomic weight is about double the atomic number, or at least differs only by zero or a small number. At the end of the series there is, however, a great difference between the atomic weight and double the atomic number.

Mr. Stephen Miall, in his little book on "The Structure of the Atom" (Benn Bros., London), has pointed out that the atomic weight w is related to the atomic number n in the manner expressed by the formula $w = 2n + b$, where b may be called the dead weight or ballast.

Van der Broek made the suggestion, adopted now very generally, that the atomic number represents the resultant number of positive electrons in the nucleus, or what is the same thing, the number of planetary electrons circulating round it in a neutral atom.

Thus the nucleus of the helium atom consists of four positive electrons bound together by two negative electrons. The resulting positive charge is then 2 units. The atomic number of helium is two, and its atomic weight is 3·99 or nearly 4. It has two negative electrons which circulate round the nucleus. In this case the "ballast" weight is zero. In the case of uranium, however, the atomic number is 92,

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the atomic weight is 238·2. Hence the "ballast" is 54·2.

One important thing discovered is that the chemical properties of the atom are more closely related to the atomic number than to the atomic weight. In short, it is possible to have atoms of identical chemical properties but different atomic weights. These atoms have been named by Professor Soddy *isotopes*. Thus, there appear to be several different kinds of atoms of the metal lead of slightly different atomic weights, but all having the atomic number 82 and all the same chemical properties.

It was long ago suggested by Prout that all atoms were built up of multiples of a certain primordial element, and hence that atomic weights should all be integer multiples of some unit. As, however, analytical chemistry progressed, it was found that this was not the case. Enormous skill and knowledge have been brought to bear of late years upon the determination of the atomic weights, and it has been found that Prout's hypothesis is not supported by facts.

Take, for instance, the atomic weight of chlorine, which is 35·46, when that of oxygen is 16. The weight of the atom chiefly resides, as we have seen, in the positive electron, and there must be an integer number of these positive electrons in the nucleus. The suggestion has therefore been made that there are two kinds of chlorine atom or two isotopes, one

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with atomic weight of 35, and the other with an atomic weight of 37. They both have the same chemical properties, and ordinary chlorine gas is a mixture of these two kinds of chlorine atoms in such proportions that the average atomic weight is 35·46.

The explanation of this may lie in the fact that small variations in the ballast weight of the atom may take place without variation in the atomic properties. Thus the atomic number of chlorine is 17. One kind of chlorine atom has an atomic weight of $35 = 2 \times 17 + 1$, and the other isotope is $37 = 2 \times 17 + 3$, and 1,300 atoms of ordinary chlorine gas comprise about 1,000 atoms weighing 35 and 300 weighing 37 units, equivalent to 1,300 in all, weighing 35·46 on an average.

It is a singular fact that, taking the oxygen atom to weigh 16, the following atoms have nearly exact integer atomic weights, helium = 4, carbon = 12, nitrogen = 14, fluorine = 19, sodium = 23, phosphorus = 31, sulphur = 32, arsenic = 75, iodine = 127, and cæsium = 133.

On the other hand, Dr. Aston, of Cambridge, working with improved methods originated by Sir Joseph Thomson, has determined with great exactness that the following elements comprise two isotopes: lithium of atomic weight 6 and 7, boron 10 and 11, neon 20 and 22, chlorine 35 and 37, argon 36 and 40, potassium 39 and 41, bromine 79

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and 81, whilst krypton, tin, xenon, mercury, magnesium and lead, have many more than two isotopes.

It appears quite clear therefore that the atomic number which gives us the total number of negative electrons circulating round the nucleus in the neutral atom is the determining factor in the chemical behaviour of the atom. It is now considered that these planetary electrons are arranged in rings or shells, one outside the other.

Thus in the carbon atom of atomic number 6, there are six resultant positive units of charge in the nucleus and two shells or rings of planetary negative electrons, the inner containing two and the outer layer four negative electrons, making six electrons in all. In the oxygen atom there are eight electrons in all, viz., 4, 2, and 2 in three shells, and in the sulphur atom there are 16 in all, arranged in four shells of 8, 4, 2 and 2, reckoning from within outwards.

The electrons in these shells or zones are in rapid rotation round the nucleus, but the different groups do not necessarily all revolve in the same direction nor in the same plane.

The outer shell or layer of negative electrons in the atom is that which chiefly determines the type of chemical compound formed with other atoms, and these are termed the *valency electrons*. Some of these valency electrons are easily detached in the case of the metallic atoms. In a mass of

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metal, say, copper, there are, therefore, free electrons which are jumping about from atom to atom and moving in the inter-atomic spaces with a velocity of approximately 50 miles per second.

25. Electric Conductivity and Electric Currents.

These free electrons bestow upon the metal its electric conductivity because when an electromotive force due, say, to a Voltaic cell, is applied to the metal, these free negative electrons are caused to drift or move as a whole towards the positive end of the conductor.

The electrons have superimposed upon their irregular motion a drift in one direction, just as a swarm of gnats, in which each insect is flying hither and thither in an irregular manner, might be blown as a whole down a street by a gentle wind. This drift of electrons constitutes what we call an electric current. Hence our usual convention as to the direction of the electric current in a conductor is wrong. We commonly say that the direction of the current in a wire is the direction of movement of positive electricity in the wire. But, in fact, there is no movement of positive electricity, only a drift of negative electrons in one direction in the wire. Hence all our usual mnemonic rules involving the direction of the current and that of the embracing magnetic field require to be restated and reversed.

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A negative electron revolving in an orbit is therefore equivalent to an electric current and produces a magnetic field. Hence atoms in which the negative electrons revolve in the same direction and nearly in the same plane will exhibit magnetic polarity, and this may account for the magnetic properties of the oxygen and iron and nickel atoms.

26. Radio-activity.

A brief reference must then be made to the special qualities of the so-called radio-active elements, of which the most remarkable is the element radium.

It is found that certain of the atoms of high atomic number break up spontaneously and gradually are transformed into atoms of lower atomic number and weight. In the case of an atom like uranium, of atomic weight 238·2, the nucleus is a very bulky thing relatively to that of the hydrogen atom, which, according to a prevalent view, consists simply of a single positive electron, with a single negative electron revolving round it. The uranium atom, on the other hand, has 92 planetary electrons, and 92 effective and probably about 240 actual positive electrons packed into its nucleus, and perhaps about 148 negative electrons as well.

As the planetary electrons revolve round the nucleus they may set up strains in it or tidal actions, which may increase to such a point that the nucleus breaks up. When this is the case, we have thrown

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off from it either one or more negative electrons called β-particles or else one or more helium nuclei called α-particles. The helium nucleus consists of a group of four positive electrons and two negative electrons, having thus two effective positive charges. These six electrons must be bound together very tightly because the helium nucleus appears to be a remarkably permanent and indestructible article.

When the nucleus is ruptured or broken up these α and β-particles are shot off with immense velocity approximating to that of light waves, viz., 300,000 kilometres per second. In addition to this the impact of a β-particle against other molecules gives rise to the production of certain very short electromagnetic waves called γ-rays, which are like the X-rays in properties.

The atoms of which the nuclei can break up in this way are called *radio-active* elements. Prominent amongst them are radium itself, thorium and uranium, all of which are atoms of large atomic weight and relatively bulky or heavy nuclei.

We all know that when a heavy flywheel is in rapid rotation it contains a store of energy measured by half the product of its so-called moment of inertia and the square of its angular velocity.

If the flywheel bursts, the fragments are flung away far and wide, generally with disastrous results. In the same manner when the nucleus of a radio-active atom breaks up its α and β-particles are hurled away with such enormous velocity that

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they break up or ionise other atoms in their neighbourhood. The nucleus may therefore be in extremely rapid rotation.

The break up of a radio-active nucleus, however, is not exactly like the bursting of a flywheel. It proceeds by many regular stages and the various intermediate atoms which are successively formed have "lives" of very different duration, varying from a few minutes to many thousands of years.

Thus, for instance, beginning with the atom of uranium, with atomic weight 238·5, its average life is 5,000 million years. It throws off an α-particle, thus reducing its atomic weight by four units, to 234·5, and is then transformed into a substance called uranium X_1. This, however, only lasts a few days (about 25) and is then transformed into uranium X_2. The latter gives off a β-particle, which does not sensibly alter the atomic weight, and is thus transformed into a far more permanent atom called uranium II., which has a life of about two million years. This, by the loss of two successive α-particles then becomes ionium and finally radium, with an atomic weight of 226·5. This in turn gives off a gaseous "emanation," which has an atomic weight of 222·5, and is often called niton. Finally, by further losses of α and β-particles, this last substance is transformed into metallic lead, with an atomic weight of 206·5.

There is another chain or series of atomic transformations starting from uranium II. which, in the

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end, also yields lead, but with an atomic weight of 210. Finally, from the thorium atom, there are a series of descendants ending also in lead, with an atomic weight of 208. Hence the lead atom exists in several isotopic forms, and there are atoms, all of which, chemically speaking, are lead, but have different atomic weights. Accordingly, some part at least of the atomic weight of lead, viz., that over and above twice its atomic number, which is 82, has no influence on the chemical properties, for all these varieties of lead atom have the same atomic number.

Thus, in a certain sense, the dreams of the old alchemists have been realised. Although we have not been able to transform lead into gold, as they hoped, we now know that the element uranium is slowly and spontaneously changed into radium and finally into lead.

It appears therefore as if the nuclei of all atoms are built up in part of the extremely permanent helium nuclei, held together in some way by negative electrons, into a very compact mass. Possibly also free positive electrons or hydrogen nuclei may be present as well.

From certain experiments made by bombarding nitrogen and oxygen gas with α-particles, Sir Ernest Rutherford has shown that nuclei or atoms of an atomic weight of three carrying one, or it may be two, positive electric charges, are liberated. It seems as if these nuclei were composed of three

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positive electrons, held together by one negative electron or perhaps two.

It has been long known that the atomic weights of many elements which are integers can be represented by the general formula $w = 4n$ or $w = 4n + 3$ where n is some integer. This seems to support the view that the atomic nuclei in these cases are built of helium nuclei of mass four and of the unnamed nuclei of mass three, the atomic number being then given by $a = 2n$ or $2n + 1$.

Harkins has suggested that all atomic nuclei are built up of hydrogen nuclei, helium nuclei, and the above unnamed nucleus of mass three, but having one positive charge and not two.

When the helium nuclei or α-particles are expelled from the disrupted nucleus of a radio-active atom, they are flung off with velocities which may be of the order of 20,000 kilometres per second, or, say, 12,000 miles per second, a velocity which would take them round the earth in two seconds. Since the mass of a helium nucleus or α-particle is about four times that of a hydrogen atom, or, say, nearly 6×10^{-24} of a gram, the energy of the α-particle is about

$$\frac{1}{2}\frac{6}{10^{24}} 4 \times 10^{18} = 12 \times 10^{-6} \text{ erg},$$

or, say, 12 microergs.

On the other hand, the β-particles are thrown off from radio-active atoms with a velocity of about

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0·9 of that of light, or, say, 270,000 kilometres per second. Since, however, the mass of an electron is only 9×10^{-28} gram, we have the kinetic energy of a β-particle given by

$$\frac{1}{2}\frac{9}{10^{28}}\left(\frac{9}{10} \times 3 \times 10^{10}\right)^2 = \frac{1}{3} \times 10^{-6} \text{ erg},$$

or nearly one-third of a microerg. Therefore the single α-particle has 30 to 40 times the kinetic energy of the single β-particle.

In consequence of their very small size and of the very porous or open structure of atoms generally, the chance of a β-particle being stopped when fired through a volume of air is much smaller than that of the larger α-particles. The β-particles scarcely lose half their velocity in passing through a thickness of air of one metre, whereas the α-particles are stopped completely by a few centimetres.

Owing to the very open or skeleton structure of atoms, which has already been mentioned, it is possible for the α-particles to pass through thin sheets of metal, but the β-particles can pass through plates of several millimetres, or even inches, in thickness.

In the passage of the particle it will come into close proximity with other atoms of the metal plate and be deflected from its path. Thus an α-particle may come close to some other atomic nucleus and will then whirl round it and be flung off in a hyperbolic path just as a comet is affected when passing

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round the sun. Similarly a β-particle will be deflected by atomic electrons.

When an α-particle strikes a screen covered with fluorescent material, such as zincblende, its impact gives rise to a tiny flash of light which can be observed through a lens or microscope. This fact was utilised by Sir William Crookes in the construction of an instrument he called a *spinthariscope*, in which a minute fragment of a radium salt on the head of a pin was held near a small fluorescent screen and the little flashes due to the bombardment of this target by the α-particles was observed through a lens.

Sir Ernest Rutherford and many other investigators have made use of this method in a highly ingenious manner to determine a maximum limit to the size of the nucleus of atoms by calculations made from observations of the deflection of an α-particle by a thin plate of metal.

By bombarding molecules of hydrogen gas in this manner with α-particles, it has been found that the centres of the hydrogen and helium nuclei must approach within a distance of $1{\cdot}7 \times 10^{-13}$ centimetre. Hence the sum of the radii of these nuclei must be if anything *less* than the above number.

We can conclude, therefore, that the diameter of a single positive electron such as forms probably the nucleus of a hydrogen atom, is *less* than $0{\cdot}8 \times 10^{-13}$ centimetre. Now this is less than the diameter of a negative electron. Moreover, since we know the

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mass of the hydrogen nucleus, which is $1{\cdot}66 \times 10^{-24}$ gram, we see that the destiny of the hydrogen nucleus or positive electron must be of the order of 7×10^{15}, an enormous number when compared with the mean density of atoms themselves, or masses of matter.

Hence we arrive at the conclusions that atoms are very open or porous structures, but the particles, viz., the positive and negative electrons of which they are made, have a stupendous density.

From experiments made by the deflection of α-particles in passing through sheets of various metals, Sir Ernest Rutherford has concluded that the diameters of the nuclei of atoms are of the order of 10^{-12} centimetre, or one-billionth part of a centimetre.

27. Electromagnetic Radiation and the Quantum Theory.

Before we can proceed to explain the manner in which the vibrations of electrons, atomic nuclei and atoms or molecules give rise to a vast gamut of electromagnetic waves stretching from the shortest X-rays up to the longest known dark heat rays, and beyond these the Hertzian and the wireless waves, we shall have to attempt the task of giving a brief sketch of the nature of the so-called Quantum Theory or hypothesis introduced into physics by Professor Max Planck about the year

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1901, which has opened a new chapter in the development of physical ideas.

It will be necessary to preface explanations by some definitions of terms and words used in the science of mechanics.

An important physical conception is that of *Energy*. Energy is defined as the ability to do *Work*, and this last is a technical term meaning the displacement of a material substance against some force which resists that displacement. Thus, if we lift up a weight against the force of gravity, we do work in this sense of the word. The work is measured by the product of the displacement and the force, each reckoned in certain consistent units. Thus, if we lift up a mass weighing 10 lbs. to a height of 10 feet, we do work against gravity to the extent of 10×10 *foot-pounds*. The time taken in doing the work does not affect its numerical value. Thus, in the above example the work done is 100 foot-lbs., whether the mass is lifted very slowly or very quickly. When the substance has been so lifted up against the force of gravity it is said to have potential energy or energy of position to the extent of 100 foot-lbs.

There are many ways in which such potential energy can be accumulated. For instance, by bending or stretching a spring, by pumping up water to an elevated cistern, or electrically, by charging with electricity a condenser or Leyden jar. In all cases the work or energy is measured

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by the product of two factors, viz., a displacement and a force, a quantity of water and a height through which it is lifted, or a quantity of electricity and the mean potential to which it is raised.

The rate at which work is done is called *Power*. Thus, if we lift up a mass of 550 pounds weight a height of one foot in one second, we do work of 550 foot-pounds at a rate called *One Horse Power*, which, however, has nothing to do with a horse.

Energy also can exist in the form of a mass in motion or some equivalent. In this case it is called *Kinetic or Motional Energy*. It is then measured by half the product of the mass and the square of its velocity.

The reason for this is as follows :—

Force is defined as any agency which changes the momentum of a body. The momentum is defined as the product of the mass and the velocity. The force is measured by the rate at which it changes momentum or by the momentum added per second.

Thus, if a body of mass m grams has a velocity denoted by v_1 centimetres per second, and after a short time t seconds, during which it is acted upon by a force f, acquires a velocity v_2, then the force f is measured by the difference $(mv_2 - mv_1)/t$, because this is the time rate of change of its momentum. During this time its velocity has changed from v_1 to v_2, and if this has taken place uniformly, the distance or space moved over by the body is

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$\frac{1}{2}(v_1 + v_2) \times t$. The work done is then the product of force and displacement or is

$$W = \frac{(mv_2 - mv_1)}{t} \times \frac{(v_2 + v_1)}{2} \times t = \tfrac{1}{2}mv_2^2 - \tfrac{1}{2}mv_1^2.$$

This shows that the work done on a mass m in increasing its velocity from v_1 to v_2 is the change in the quantity $\frac{1}{2}mv^2 = \mathcal{T}$, called the kinetic energy.

The above statement may be regarded as valid in accordance with Newton's Laws of Motion and his doctrine of absolute space and time. The searching analysis to which the ideas of space, time, and motion have been submitted by Einstein and his followers have, however, shown the necessity for modification in our fundamental conceptions. The basis on which these new views have arisen was the inference made from the experiments of Michelson and Morley, and from other observations, which demonstrated clearly that the velocity of a ray of light is independent of the motion of the source of light or of the observer, and in fact is the same for every frame of reference. The velocity of light is therefore a fundamental constant of nature. It is always and everywhere 300,000 kilometres per second or very close thereto. We denote this velocity by the letter c.

Experience also shows us that our statements about the facts of nature have in general identical form whether we refer them to one frame of reference or to another in uniform relative motion with

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respect to it. Thus, if a scientific man had a laboratory on board a ship and made measurements of the time of vibration of a certain pendulum or the space fallen through in one second by a released ball, he would find exactly the same numerical results whether the ship was at rest in harbour or moving smoothly and uniformly over the sea at any speed. This is called by Einstein the *restricted principle of relativity*.

In accordance with this theory it can be shown that the kinetic energy of a mass m moving uniformly with a velocity v should be given by the expression $mc^2 \left\{1 - \frac{v^2}{c^2}\right\}^{-\frac{1}{2}}$ where c is the constant velocity of light. If v is small compared with c the energy is equal to $mc^2 + \frac{1}{2}mv^2$. Hence we see that even if a mass is at rest with reference to a certain frame of reference it is not therefore destitute of kinetic energy.

Furthermore, it can be shown that if an amount of energy E in the form, say, of heat is given to a body of mass m without altering its velocity of translational motion v, its energy is increased by an amount $\frac{E}{\left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}}$, and therefore its total energy is expressible as—

$$\frac{\left(m + \frac{E}{c^2}\right)c^2}{\sqrt{1 - v^2/c^2}}.$$

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This implies that the apparent mass m is increased by an amount E/c^2 by the addition of the energy E. This seems to suggest that what we call the mass of a body is only a manifestation of energy of a certain kind, possibly some form of spinning or rotational energy, and that the indestructibility of Energy and of Matter are only two different aspects of the same fact.

As long as the velocity of translation of a mass is small compared with that of light the increase in its kinetic energy, which results from giving it a velocity v, is expressed by $\frac{1}{2}mv^2 = \mathcal{T}$, and this, in ordinary classical theory, is taken to be its kinetic energy, although the theory of Relativity shows that it is not the whole of it. There is, in addition, in connection with a mass m a concealed or latent kinetic energy measured by mc^2, even when that body is at rest with respect to the framework of reference considered.

Suppose, then, that a massive body like a planet is moving along a certain path with a certain kinetic energy at each point. Let us suppose the path divided up into little elements of length, each denoted by the symbol ds, and let each element of length be described in a short time, denoted by dt. Then the velocity of the body in each little stage is measured by the quotient ds/dt and the kinetic energy by $\frac{1}{2}m\left(\frac{ds}{dt}\right)^2$, if we call the mass m.

If we multiply the mean kinetic energy during

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each element of motion by the time dt taken to describe it, we obtain the product—

$$\tfrac{1}{2}m\left(\frac{ds^2}{dt}\right)dt \text{ or } \tfrac{1}{2}m\frac{ds}{dt}ds \text{ or } \tfrac{1}{2}mvds.$$

If we obtain these products for each little element of the path and then add them all together or integrate over the whole path, we obtain a numerical result which measures the so-called *Action* of the body.

It appears that there is a certain kind of equivalence between the product of a small quantity of energy stored up or existing for a long time, and that of a larger quantity of energy for a relatively shorter time, provided the product of energy and time of action is constant.

What may be called the value of the energy for physical purposes or the opportunity of using or transforming a certain amount of this energy is not merely measured by its numerical amount, but by the product of its amount and the time it is available.

Thus, to give an analogy, there is a certain sense in which a small sum of money placed at one's disposal to use for a number of years may be the equivalent of a larger sum placed at one's disposal to use for a lesser time, viz., when the product of money and years is the same in each case. It appears, then, that in physical phenomena and changes the all-important matter is the totality of

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the Action. In a large class of physical phenomena the spontaneous operations always take place in nature in such a manner that the Action expended or exerted is the least possible.

This principle of Least Action is of very wide application in dynamics. Thus, a planet moves in its orbit round the sun along a path such that the Action in going from one point to another is the least possible. There is a corresponding principle of Least Time in optics. A ray of light moves through a medium with a velocity which is inversely as the index of refraction (denoted by μ) of that medium. Hence the time of travelling over an element of path ds is the product μds. The path of a ray of light through a series of transparent media is always such as to make the sum of the elementary products μds a minimum. We know that energy is capable of existing in many different forms, and that these can be transformed into each other according to certain equivalents. Thus the kinetic energy of a moving mass can be transformed into its equivalent in heat or energy of atomic motion, and the same for chemical or electrical forms of energy. When we are dealing with large scale phenomena, or motions of large masses these transformations of Energy or changes of Action appear to be able to take place quite continuously and in any amount large or small. Moreover, in the case of the dynamics, or motion under forces, of large masses, the laws of motion

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enunciated by Galileo, Kepler and Newton are able to give a satisfactory explanation of phenomena. When, however, we are dealing with the mechanics of a single atom or with very small scale phenomena, especially with radiation of energy, there is good evidence that we require to modify the classical dynamics by some other assumptions or postulates. This is especially the case with respect to radiation of energy by electrons.

The important innovation introduced by Planck in 1901, in connection with radiation phenomena, was the idea that Action is then discrete in nature and that there exists what may be called an *atom of action*, or least possible indivisible amount of it.

We cannot explain why this should be the case. We have seen that electricity is also atomic in structure and that there exists an atom of electricity called the electron, equal to $4{\cdot}77 \times 10^{-10}$ of an electrostatic unit or to 16×10^{-20} of a coulomb or ampère-second, which is indivisible. All charges of electricity must be in integer multiples of this electron unit. We can have them in millions or billions, but we cannot have a fraction of a unit or of an electron.

Planck has suggested that radiation of energy from atoms can only take place in integer multiples of a very small unit of Action which is equal to $6{\cdot}547 \times 10^{-27}$ erg-seconds. This means $\frac{6547}{10^{30}}$ of an erg of energy lasting for one second or one erg

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lasting for the same fraction of a second. The reader may be reminded that one erg is the work done when a force of one dyne acts through a distance of one centimetre.

The *weight* of a mass of one gram is nearly 981 dynes. The above unit of action is an extremely small one and we need take no account of the atomicity of action in large scale dynamics, but only when we are dealing with atoms singly.

Planck and also Bohr have applied this view of the atomicity of action to the discussion of the problem of radiation of electromagnetic waves by electrons and atoms. When a solid body, say, a mass of carbon or metal, is raised to a high temperature, its atoms and electrons are thrown into a state of rapid vibration. Planck calls these vibrators oscillators.

If we consider a single electron moving to and fro along a straight line with a vibratory motion, we see that its velocity is changing at every instant, and therefore, in accordance with explanations already given, the electron is sending out vibrations along its electrolines or lines of electric force; in other words it is radiating energy. It is very easy to prove that in the case of an electron oscillating in one line like the bob of a long pendulum, the Action in one vibration is the product of the mean energy of motion and the periodic time. Also that the energy radiated per period is a definite fraction of the oscillating energy. If T is the time of one complete

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vibration, and if in that time an amount of energy denoted by E is radiated, then the Action is the product of E and $\mathcal{T}$ reckoned in ergs and seconds.

Planck then says that the product of E and $\mathcal{T}$, or $E \times \mathcal{T}$, must be an exact integer multiple of the unit of action which is denoted by h ($= 6{\cdot}55 \times 10^{-27}$ erg-seconds). Therefore we have the equation $E\mathcal{T} = mh$ where m is some integer. But if the frequency of the oscillations or number per second is n, then $n = 1/\mathcal{T}$ and $E = mnh$. Accordingly, radiation of energy appears to take place in integer multiples of a unit of energy equal to the product nh. This unit is called a *Quantum* and is denoted by the Greek letter ε.

Planck's fundamental equation is then

$$\varepsilon = nh.$$

The reader should carefully notice that the magnitude of this quantum of energy (ε) is not constant but is proportional to the frequency n. It is the atom or element of Action denoted by h which is invariable in magnitude.

The upshot of all the above is as follows: If there are a number of little oscillators or vibrating electrons which vibrate with different frequencies, like pendulums of different lengths, some moving fast and some slow, or with high frequency and low frequency, then each of these electric oscillators is radiating energy, but they can only radiate this energy in whole quanta and the size of the

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quantum radiated in each case is proportional to the frequency.

In an incandescent body the electrons and atoms which constitute the oscillators, do not all possess the same energy of vibration, any more than the molecules of a gas have the same velocity. The speeds of the gas molecules and also the energies of the oscillators are distributed according to Maxwell's law, as already explained, and according to a similar law the energy is distributed between oscillators having the same frequency.

Let us consider, then, the condition of things in a mass of incandescent metal or carbon. We have atoms and electrons which can vibrate in very various periods depending on their mass and the elastic constraint to which they are subjected by the attractions and repulsions of neighbouring electrons. Moreover, they are vibrating with different amplitudes, or in other words have different amounts of energy associated with them. We may, in imagination, divide these oscillators into groups arranged progressively according to the frequency of their oscillations, and each group of similar frequency may be considered as divided into sub-groups, which have similar amounts of oscillatory energy, but the sub-groups arranged in order of increasing energy content. Each of these oscillators is sending out electromagnetic waves of identical frequency and of various amplitudes. This electric radiation constitutes the light, heat and actinic radiation of the

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incandescent body. If then we send a thin beam of this radiation through a prism or defraction grating, these rays of different frequencies are differently refracted and spread out into a spectrum when received on a screen.

As regards those waves, the wavelengths of which lie between 0·395 μ and 0·76 μ, or, say, 3,950 Angström units to 7,600 A.U., these have the power of stimulating the retina of our eyes and exciting the sensation of light, the short waves creating a sensation of violet light and the larger red light. It is, however, well known that there is a range of ultra-violet light or invisible rays of wavelengths lying between about 250 A.U. and 4,000 A.U., which can impress a photographic sensitive plate, but not our eyes. Again, there is a range of longer ultra-red or so-called dark heat rays, extending in wavelength from 0·8 μ to about 300 μ, all the waves in which cannot affect our eyes but can heat a sensitive thermometer.

Suppose, then, that we form a spectrum, that is, expand the complex many-frequency radiation from an incandescent body, such as the light and heat from an electric arc lamp or from the sun, into a spectrum or band of radiation, every strip of which is formed by waves of one particular wavelength. Let us place across this band a blackened platinum wire. This wire will absorb all the energy at that point and be heated thereby. We can determine the temperature of the wire by the

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increase in electric resistance that then takes place. So used this wire is called a bolometer wire and it enables us to measure the energy associated with the waves of each particular radiation from the least unto the greatest wavelength (see Fig. 46).

When this measurement is made we find that the waves of very large wavelengths or very small frequency have little or no energy and that as the

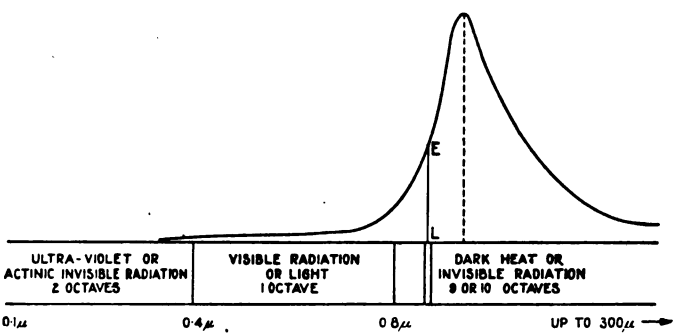


FIG. 46.—Radiation energy curve for the spectrum of visible and invisible radiation. The height of the ordinate of the curve at any point is a measure of the energy of the radiation at that point.

frequency increases the energy of radiation increases also, but not indefinitely. It increases up to a certain wavelength of maximum energy and then begins to fall off again, so that the waves of very high frequency have also small energy associated with them.

We can thus plot a radiation energy density curve in terms of wavelength or frequency, as in Fig. 46.

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When we attempt to account for this form of this curve, and especially for the fact that it has a maximum ordinate for a certain wavelength, difficulties are found. As long as we assume that energy can be radiated continuously, that is, in any amount per second from each oscillator, theory shows that the radiation energy should increase rapidly with the frequency so that oscillators of high frequency should radiate very much more energy than those of low frequencies, whereas in the normal spectrum it is found that the waves of very high frequency have small energy as well as the waves of very low frequency.

Planck's theory of energy quanta was devised therefore originally to meet this difficulty and to enable a formula to be found which will express or predetermine the curve of radiation energy along the spectrum. This it has done very successfully. He assumes, as we have seen, that energy is not radiated continuously by the oscillators, but comes out, so to speak, in gushes or quanta, the size of the quantum being in the case of every oscillator proportional to its frequency of oscillation or number of vibrations per second. Hence for the high frequency oscillators the quantum will be large and the probability that any particular oscillator or many such oscillators will have this amount of energy at disposal is small. Hence the total energy contribution of the high frequency oscillators is small. On the other hand, the quantum

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for the low frequency oscillators is small and therefore nearly every one is capable of giving it, but then, owing to the smallness of the unit, the total energy contribution is again small. But for oscillators of medium frequency the total contribution may be, and is, much larger. Hence we get for a certain wavelength, a maximum energy radiation.

We might give an illustration as follows :—

Suppose that a collection was being made in a church or in a number of churches for some charitable object, say hospitals. Imagine that in one church the clergyman announced that no person must give a donation of more or less than £5. The chance of there being many persons present who had that amount in their pockets and were willing to give it in one lump sum might be small and hence the total offertory would be small also, comprising perhaps only one or two such donations.

On the other hand, imagine that in another church the minister announced that no person must put more or less than one penny in the plate. Nearly everyone would be able to give this coin, but the unit being small, the total offertory would again be small. If, however, an intermediate sum, say, one shilling or one half-crown, was announced as the sum which was to be the donation unit, a large number of the congregation would be able to give this amount and hence the total offertory would be much larger than in the extreme cases in which the unit of donation was either one penny or five

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pounds. By this ingenious idea Planck was able to find a formula which when represented graphically, exactly agrees with the experimentally determined curve of radiation energy distribution in the spectrum, and no one had previously been able to achieve this result.

Nevertheless, Planck's theory seems to necessitate certain assumptions which are rather forced. We have no proof that in an incandescent body there are oscillators of every possible frequency, in short, oscillators of an infinite number of frequencies. Also it is difficult to form any clear idea why Action should be atomic in structure unless Space and Time are also in discrete indivisible units.

In the spectrum there are, however, an infinite number of rays of different frequency and wavelength, extending from the longest dark heat rays yet observed of wavelength about 200 to 300 μ, to the shortest ultra-violet rays of about 0·1 μ in wavelength. Moreover, the spectrum may be said to extend to infinity in both directions, for beyond the longest dark heat waves we have the Hertzian and wireless waves to be considered in our next chapter, and beyond and below the shortest ultra-violet waves we have the X-ray waves.

A way out of this difficulty has, however, been suggested as follows: The process of radiation in an incandescent body probably consists in the creation of sudden groups of complex vibrations of finite duration, caused by the impact of electrons

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against atoms, and these last in turn are set in vibration as a whole and in their component electrons. These complex vibrations may by Fourier's theorem, already explained, be regarded as made up of a large group of simple harmonic vibrations each of different frequencies.

Since the complex groups of vibrations which can thus be analysed are not produced simultaneously and in step or phase or absolute agreement with each other, we have in fact sent out from the incandescent body an infinite number of trains of complex vibrations which are built up of an infinite number of component harmonic vibrations, and the prism or diffraction grating separates these out from one another and spaces them in order of wavelength or frequency in the observed spectrum of the radiation.

Planck's quantum theory has been applied by N. Bohr in a highly ingenious manner to explain the line spectrum of hydrogen gas. When we pass an electric discharge through rarefied hydrogen, and examine and photograph the spectrum of the emitted light it is found to consist of a number of lines separated from each other. In other words, the light radiated does not consist of rays of every possible wavelength, as in the case of an incandescent solid, but of light of certain definite wavelengths, which follow a particular law of interval. We have seen that the hydrogen atom probably consists of a negative electron which revolves round a positive nucleus like a planet round the sun.

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According to the deductions of ordinary theory, based on Newton's laws of motion, the revolving electron is being accelerated, that is, has its velocity changed in direction continually. It should, therefore, create waves in the æther or radiate. This should reduce its angular energy, and it ought, therefore, to be continually falling nearer to the positive nucleus and continually increasing its speed of revolution, and therefore the frequency of its radiation. The vibrating electron should therefore emit a continuous spectrum, but it does not do this. Hence, Bohr has made the suggestion that an electron cannot revolve round a positive nucleus at any distance from it, but only in certain orbits, which are called quantum paths, and that when travelling in these orbits it does not create æther waves or radiate. These orbits are such that the angular momentum of the electron corresponds with a definite integer multiple of Planck's constant h.

The electron can, however, be jerked or displaced by an impact from one quantum orbit to another, and when this is the case it radiates a definite quantum of energy corresponding to the difference between the action of the two quantum paths.

We have not yet been able to see any more fundamental reason for the existence of these quantum orbits, but the fact remains that by this supposition Bohr has been able fully to explain the

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production of the hydrogen line spectrum, which cannot be done as long as we apply to the electrons revolving around the nucleus the Newtonian laws of planetary motion.

28. Atomic Energy and its Release.

The previous explanations will have made it clear that the nucleus of the atom in which its gravitative mass chiefly resides is a structure which is probably built up of helium and hydrogen nuclei and of unnamed nuclei of mass three times that of the hydrogen nucleus, which are powerfully held together by negative electrons into a very compact mass. The helium nucleus in particular seems to be a very strong structure.

It appears that a very large amount of energy has to be put into the ultimate ingredients, viz., the positive and negative electrons, to bind them together in this extremely firm manner, so as to make a very small but exceedingly dense mass of matter about 10^{-12} or 10^{-13} of a centimetre in diameter. We might regard the nucleus as a sort of clock-spring which has been coiled up very tightly by the exertion of energy and then bound in some manner not easily released. If, however, certain kinds of atomic nuclei such as those of nitrogen are bombarded by α-particles, the nucleus is disrupted and its approximate constituents, viz., helium and hydrogen nuclei, are flung out with great velocity.

This, and the phenomena of radio-activity, has

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suggested that we have in the nuclei of atoms an enormous store of energy which in some way we may be able to release.

At the present time, if we set on one side the not very large stores of water power which are often in very sparsely inhabited places, the chief sources of potential energies lie in the stores of coal and oil in the earth's crust. But the oil represents but a fraction of the energy stored up in the coal or to be obtained by burning the coal. Hence we may say that the chief source of power in the world is the potential energy of its stores of coal.

Nevertheless, the increasing cost of raising and transporting it, owing to the increase in the cost of labour, creates the hope that in some way the human race may be able to tap this almost illimitable store of atomic energy. The prospects, however, at present are not very bright. Such small achievements in direction which have been accomplished have required the expenditure of the expensive element radium.

Having regard to the fact that the atom is probably a wholly electrical structure, it may perhaps be possible to break it up by means of suitable high frequency electric oscillations, to the study of which we shall next direct attention.

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CHAPTER V

THE PRODUCTION AND DETECTION OF LONG ELECTRIC WAVES

29. Electric Oscillations.

As already stated, we have reasons for believing that in metals, carbon, or other substances which are conductors of electricity, there are free electrons which are moving irregularly with very high speeds in the interstices of the atoms of matter, or jumping from atom to atom.

Conductive materials such as metals are built up of atoms which easily lose one or more electrons from their outer shells or orbits. These detachable electrons are called the *valency* electrons, and it is probably one or more of these that become free to roam about in the inter-atomic spaces.

From certain facts we can infer that in a metal there are about as many free electrons as there are atoms in any given volume. In those substances we call non-conductors, but which Faraday appropriately named *dielectrics*, such as glass, ebonite, paraffin wax, mica or shellac, the number of free electrons is very small, but under the action of electric force certain of the electrons in the atomic orbits or structure can be displaced or strained

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elastically, so that when the electric force is removed they spring back to their old positions in the atoms.

We can thus cause in metals and conductors generally, by means of electric force, a drift of the free electrons which is called an electric current, but in dielectrics we can only produce an electron displacement or strain. The drift motion of the electrons in the case of the electric current creates, as we have seen, a magnetic force which is distributed round the conductor in closed lines embracing it. In the case of a straight wire conveying an electric current with return wire at a considerable distance, the lines of embracing magnetic force due to the drifting electrons are circles whose centres are in the wire and whose planes are perpendicular to it.

In considering this effect called electric displacement in dielectrics, Clerk Maxwell, whose scientific thought on this subject was epoch-making in its importance, saw that it would be logical to conclude that an electric displacement *whilst it was being made or removed* was equivalent to an electric current and should therefore produce a magnetic field in the same way as does a conduction current in conductors. We have then to distinguish between conduction currents and displacement currents in one sense, but in another they are quite identical and both involve the production of a magnetic force or field embracing the current.

Let us next consider a compound circuit comprising a sheet or layer of dielectric, say glass, contained

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between two sheets of metal, made in fact like a sandwich, the meat being the glass and the two slices of bread the metal sheets. Such an arrangement is called a condenser or Leyden pane (see Fig. 47).

Suppose we give to one sheet of metal a charge of negative electricity. This implies that we force into it an excessive number of free electrons over and above those naturally present in it.

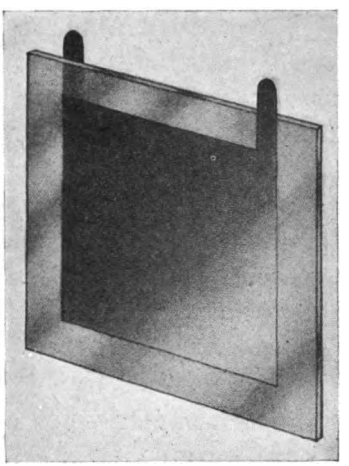


FIG. 47.—A Leyden pane or electrical condenser, consisting of a sheet of glass or other dielectric partly covered on both sides with tin foil or sheet metal.

Owing to their mutual repulsion the result is that the displaceable or mobile electrons in the sheet of glass are all strained or displaced as far as possible away from this electron super-charged metal plate. Also the free electrons in the other metal plate move as far away as possible from the super-charged plate. If this extra electron charge has been given by an electrical machine or by a battery, it implies that at the opposite pole of this battery or electrical machine there is a deficit of electrons. Hence, if we connect this last named pole with that plate of the condenser which has

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not been charged with extra electrons, a number of electrons equal to the excess in the other plate will return to the battery or electrical machine, whilst the plate itself is left with a deficiency of free electrons.

As regards the condenser the state then is, that in one metal plate there is an excess of free electrons, in the other plate a deficit, and in the intermediate dielectric plate of glass the mobile electrons are strained or displaced from their normal positions in their atoms, and this elastic displacement represents a store of potential energy, just as does a stretched or bent steel spring. The condenser is then said to be charged or have energy stored up in it. The energy of that charge is measured by half the product of the charge, reckoned in extra electrons, of one plate and the potential difference or voltage between the two plates.

The reader should note that in electrical phenomena the potential difference of two points is the exact analogue of the temperature difference in thermal or heat phenomena, and of difference of level or pressure in the case of hydraulic effects or flow of water.

In the next place let us suppose that the two metal plates of the condenser are connected by a metal wire. The result is that electrons begin to drift through this wire from the plate which has an excess of them to the plate which has a deficiency

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of them, and at the same time the electrons in the dielectric or glass plate which are strained or displaced begin to return to their normal positions. The return of electrons is, however, not merely by a uni-directional motion.

Suppose that instead of connecting by a wire two conductors are having respectively an excess and a deficit of electrons in them, we were connecting by a wide pipe, in which was a tap suddenly opened, two vessels, in one of which there was an excess of air under pressure, and in the other a partial vacuum or deficit of air. On opening the tap the air in the full vessel would rush over into the empty one, but owing to the mass or inertia of the air it would at first overrush and then rush back again and equilibrium of pressure would only be established after a series of to and fro rushes of air each less than the last. These are called aerial oscillations.

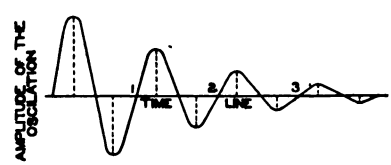


FIG. 48.—A graph or delineation of a damped electric oscillation.

In exactly the same manner, if we connect suddenly the two plates of a charged condenser, the electron equilibrium or equality is only established after a series of rapid movements of electrons to and fro in the wire which gradually die away. These are called *electric oscillations* and are in fact brief currents of electricity alternately in one direc-

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tion and then in the opposite, which decrease at each reversal. This is termed a damped train of electric oscillations. It can be represented by the ordinates or heights of a periodic but decrescent curve, as in Fig. 48, in which horizontal distances represent time and vertical distances the current in the connecting wire.

There are then two terms which must be defined as regards the condenser and the connecting wire and these are *capacity* and *inductance*.

If we wished to measure in a certain way the capacity of an airtight vessel we might state it as the weight or quantity of air that the vessel would hold when pumped full up to one atmosphere of pressure or, say, $14\frac{1}{2}$ lbs. per square inch. In the same manner we define the electrical capacity of a condenser as the quantity of electricity it holds when the potential difference of its plates is one volt or one unit.

The exact relation between the quantity of electricity Q or number of excess electrons in the negative plate, the potential or pressure difference V of the plates and the capacity C is expressed by the equation,

$$C = \frac{Q}{V}$$

or numerically, capacity is measured by quantity divided by voltage. The consistent units in which these things are measured are, voltage in volts, quantity in coulombs, and capacity in farads. As,

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however, the capacity of a condenser of one farad is extremely large, its millionth part, called a *microfarad*, is usually taken as the unit of capacity. We have seen that the quantity called a coulomb is equal to six million billion electrons; so that a condenser has a capacity of one microfarad when, if six billion excess electrons are put on one plate, the potential difference of the plates becomes one volt, or about 2/3rds of that of the poles of a single dry Leclanché battery cell.

In the next place as regards the wire with which we connect the plates of the condenser. It has two special qualities which can be measured in appropriate units. These are, first, resistance, and secondly, inductance. The electric resistance of a conductor is that quality of it in virtue of which the electric current energy is converted into heat in the wire.

Now this heat consists in part in the energy of irregular motion of the free electrons in the wire, and the electric current is the regular or unidirectional drift or movement of the free electrons in the wire, which is super-imposed on the irregular motion.

As the electrons are struggling along in one direction in the wire under the guidance and pressure of the electromotive force urging them, they are continually bumping up against the atoms of the metal and against one another and having their own course changed and some of the energy of

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their drift or regular motion converted into energy of irregular motion or heat.

The greater this irregular motion, that is, the higher the temperature of the wire, the less in general is the effect of the electromotive force in producing a uni-directional drift. This means to say that for a given electromotive force the current is less; in other words, the electrical resistance is greater.

On the other hand, the lower the temperature of the wire the less is the irregular motion of the free electrons and the greater is the uni-directional drift under a given electromotive force. Hence the electric resistance of pure metals is found to decrease with fall of temperature.

The matter is, however, a little more complicated than the above statements imply. We may regard these free electrons in the metal as the molecules of a kind of gas, and, as in the case of gas molecules, their irregular velocities are different, some moving fast and some slow. The velocity is distributed in accordance with Maxwell's law for gas molecules, and the electrons have a certain mean free path between collisions with each other and with the atoms. It is only during the time of this mean free path that the impressed electromotive force is able to act upon them and impose the drift motion in one direction, which constitutes the electric current.

If we call N the number of electrons per cubic

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centimetre, and u the drift velocity of each parallel to the axis of the wire and X the electric force acting on the electron, then the electric current I per square centimetre is measured by the product Neu. If t is the time between two collisions and m the mass of each electron, then the drift velocity acquired in the free time between two collisions is $\frac{1}{2}X\frac{e}{m}t = u$. Again, if l is the mean free path and v is the average irregular velocity of the electron, we may take l to be equal to the product vt, and if the drift velocity u is small compared with v, then the current I is given by the equation

$$I = \frac{1}{2}\frac{NXe^2lv}{2mv^2}$$

But mv^2 is twice the kinetic energy of the electron due to the irregular motion.

If we regard these free electrons as forming a kind of gas, then from the kinetic theory of gases we know that the average energy of a gas molecule is proportional to the absolute temperature T, that is, to the temperature measured from the absolute zero, which is 273° below zero Centigrade.

Hence, to convert temperatures measured on the Centigrade scale into absolute temperatures, we add 273° to them if the Centigrade temperature is above zero Centigrade, viz., the melting point of ice, and if the Centigrade temperature is below zero Centigrade we subtract it numerically from 273° to obtain the absolute temperature.

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Thus + 15° C. = 288° abs.,
but — 180° C. = 93° abs.

If then we consider the same holds good for the free electrons, we see from the previous equation that the ratio of electric force X to current I, which is a measure of the electric resistance of the cubic centimetre of the metal, is proportional to the absolute temperature, and therefore falls with it.

Experiments made in 1893 by the author, in conjunction with Sir James Dewar, showed that in the case of pure metals when cooled in liquid air to about 80° absolute, there was a fall in electric resistance approximately proportional to the decrease in absolute temperature, but other experiments made subsequently by Sir James Dewar with liquid hydrogen, giving low temperatures, and later on at still lower temperatures by Prof. H. Kamerlingh Onnes, of Leyden, in Holland, with liquid helium at a temperature of about 4° absolute, showed that the resistance of pure metals at very low temperatures does not decrease continually according to the same law. For many metals the electrical resistance tends to a minimum constant value at temperatures near the absolute zero. On the other hand, in the case of certain metals in a state of great purity such as mercury, tin, thallium and lead, the electric resistance at temperatures near 5° absolute suddenly falls from a finite value to a nearly zero value. Thus, in the case of lead

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at about 7° absolute resistance very suddenly decreases, and at a temperature of 2·45° absolute its electrical resistance is only 50-millionths of that which it has at 273° absolute, or at 0° Centigrade, the melting point of ice. In this condition the metal becomes, as Onnes calls it, a *super-conductor*. In this state very large currents may be passed through the intensely cooled metallic wire without creating in it any heat, because it has little or no resistance.

Moreover, if a powerful magnetic field is made to traverse a ring of lead in the state of super-conductivity and then is withdrawn, an electric current, called an induced current, is generated in the ring which lasts for several hours, whereas at normal temperatures it would not last more than a fraction of a second.

A wire, which is a conductor of electricity, possesses, however, another quality called *inductance*, also due to the properties of these little free electrons which swarm in it. We know that a heavy object, such as a motor-car or railway train, when once set in motion cannot be instantly stopped. In consequence of its mass (m) and velocity (v) it possesses, as already experienced, kinetic energy measured by $\frac{1}{2}mv^2$. This energy has to be used up in overcoming friction or some resistance, or in doing some form of work before the velocity can be reduced to zero. We have seen also that an electron in motion possesses electric mass,

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and hence when in motion has a store of kinetic energy.

Accordingly an electric current in a conductor, which is a procession of electrons moving together in one direction, acts as if it were a massive body, and cannot be instantly started or arrested. If i is the current in a conductor at any instant, then the energy stored up by it in the form of an electro-magnetic field is measured by the quantity $\frac{1}{2}Li^2$ where L is called the inductance or electric inertia of the circuit.

The current energy depends upon two factors, viz., the current i and the inductance L, just as the kinetic energy of a moving mass depends upon the mass m and the velocity v.

By analogy we can see that if the electric current energy $\frac{1}{2}Li^2$ corresponds to motional energy $\frac{1}{2}mv^2$, then the product Li corresponds to mv or to the momentum of the moving body. The product of inductance L and current i is called the *electric momentum.* Again we have shown that when a mass is set in motion by a force, the latter is measured by the rate at which it produces or destroys momentum. Hence again by analogy, when an electric current is changing, the electromotive force corresponding to this change must be measured by the time rate of change of the electric momentum or of Li. It can be shown that this electric momentum is a measure of the number of

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its own lines of magnetic force which are self-linked with the circuit.

It is convenient to denote the rate at which a quantity is changing with time by a *dot* put over the letter which denotes the quantity itself. Thus, if P stands for the population of a country at any moment, $\dot{P}$ stands for the rate at which it is increasing, and $-\dot{P}$ for the rate at which it is decreasing by births, deaths, and immigration or emigration.

Let us return then to the consideration of the case of the charged condenser which is discharged by connecting its plates by a wire. The instant the plates of the condenser are joined by the wire a current begins in it which is a flow of electrons. These electrons come out of the condenser plate which is charged with extra electrons. Let q be the quantity of electricity represented by these electrons, then $-\dot{q}$ denotes the rate at which they are decreasing, and this is the same as the rate at which they are flowing through the wire, which is the current x in that wire. But if C is the capacity of the condenser and v the voltage or potential difference of the plates, then $Cv = q$ and $-\dot{q} = x$ where $-\dot{q}$ denotes the time rate of decrease of the condenser charge.

But we have seen that when the current is changing the product $L\dot{x}$ denotes the effective electromotive force or voltage corresponding to that change. Therefore, we must have $L\dot{x} = v$, and

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combining this with the previous equation we have a relation between the current x and its rate of rate of change expressed by the equation

$$-LC\ddot{x} = x \text{ or } \ddot{x} + \frac{1}{LC}x = 0$$

where $\ddot{x}$ denotes the *rate of rate of change* of x.

It has also been pointed out that when a charged condenser is discharging through a wire of very small or negligible resistance the discharge is oscillatory, that is, consists in a flow of electricity or movement of electrons backwards and forwards in the wire.

It is important to obtain an expression for the number of these oscillations per second in terms of the quantities L and C.

Whenever we meet with a mathematical expression or equation of the type $\ddot{x} + Ax = 0$ it always means the x is something which fluctuates in a manner similar to the motion of the bob of a very long pendulum, or which executes a simple harmonic motion like the prong of a tuning fork.

We must, therefore, obtain a mathematical expression for the time of vibration of a simple pendulum consisting of a small bob of mass m hung at the end of a slender rod or wire of length l.

When such a mass swings or vibrates about a point like a pendulum the product of the mass m and the square of the length l of the rod or ml^2 is called the *moment of inertia* of the arrangement.

If the pendulum at any moment during its swing

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is deflected from the vertical through a *small* angle θ, then the rate at which this angle is changing with time, denoted by $\dot{\theta}$, is called the *angular velocity*. The product of the moment of inertia and angular velocity or $ml^2\dot{\theta}$ is called the *angular momentum*. The rate at which the angular momentum is changing, denoted by $ml^2\ddot{\theta}$, is a measure of the *torque* or couple causing or retarding rotation.

But we can obtain another expression for this torque or couple as follows :—The couple causing oscillation is the product of the length of the pendulum l and the resolved part of the weight of the bob at right angles to the length, viz., $mg\ Sin\ \theta$, where g is the acceleration, produced by gravity. If, however, the angle of displacement is small, then in place of $Sin\ \theta$ we can write θ, and the torque is $mgl\theta$. Equating the two expressions for this torque, viz. :—

$$ml^2\ddot{\theta} = mgl\theta$$

we have $\ddot{\theta} = \frac{g}{l}\theta$.

It will be seen that this expression for the angle of deflection of the vibrating pendulum at any instant is of exactly the same type as that for the current in the case of the discharging condensers, viz., $\ddot{x} = \frac{1}{LC}x$, only for the pendulum the quotient g/l takes the place of $1/LC$ for the condenser.

We can now obtain an expression for the time of vibration as follows : When the pendulum is at the

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extremity of its swing, it is for the moment at rest, and its potential energy is measured by the product of the mean torque and the angle of extreme displacement or by $\frac{1}{2}mlg\theta^2$.

But if s is the semi-arc of displacement or the distance of swing on either side, then $s = l\theta$, so that the potential energy is measured by the value of $\frac{1}{2}m\frac{g}{l}s^2$.

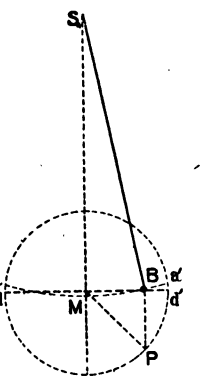


FIG. 49.—Diagrammatic representation of the swing of a bob of a pendulum.

Again, if we describe a circle with centre at the mid point M of the swing and radius equal to the swing (see Fig. 49), and suppose that a point P in this circle moves round it with a uniform velocity equal to the velocity of the bob at the middle point of its swing, then it is easy to see that the displacement of the bob at any instant is given by the projection of this point on the diameter of this circle, and if the swing is small this diameter dd^1 of this circle coincides nearly with the arc aa^1 of vibration. Hence, if T is the time of one complete revolution of this point P, T is also the time of one complete oscillation of the pendulum.

The velocity of the bob at the lowest point of its swing where it is a maximum is therefore expressed by $2\pi s/T$, where π is the circular constant 3·1415 . . .

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or ratio of diameter of the circle to its circumference. Hence the maximum kinetic energy of the pendulum must be equal to $\frac{1}{2}M\frac{4\pi^2 s^2}{T^2}$ and this must by the principle of conservation of energy be equal to the maximum potential energy at the extremity of its swing, viz., $\frac{1}{2}M\frac{g}{l}s^2$. Therefore we have

$$\frac{4\pi^2}{T^2} = \frac{g}{l} \text{ or } T = 2\pi\sqrt{\frac{l}{g}}$$

as an expression for the time of vibration.

If we represent the reciprocal of T or the number of swings per second or per unit of time by the letter n, then this is also called the *frequency* of the oscillations, and from the above equation we have for the simple pendulum

$$n = \frac{1}{2\pi}\sqrt{\frac{g}{l}}.$$

A little thought will then make it evident that since the previous discussion has shown that $1/LC$ for the condenser circuit corresponds to g/l for the pendulum, the frequency of the oscillations of a condenser of capacity C discharging through a wire of low resistance and of inductance L is given by the expression

$$n = \frac{1}{2\pi\sqrt{LC}}.$$

To make use of this formula in practice we have to measure C and L in appropriate units. In wire-

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less telegraphy and telephony condensers are used, the capacity of which it is convenient to measure in *microfarads*. Also the inductances of coils of wire employed are conveniently measured in units called *millihenrys*.

To create oscillations in such a condenser circuit, one mode is to cut the discharging wire at some place and furnish the ends with polished metal balls called spark balls, placed about one or two millimetres or so apart. The other ends of the two wires are connected permanently with the condenser plates (see Fig. 50). We then connect these balls with the terminals of an electrical machine or induction coil in operation; the plates of the condenser will be charged, one, as already explained, will have an excess of negative electrons forced into it, and the other will have a deficit.

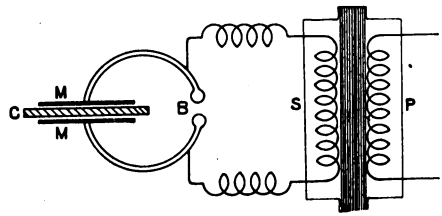


FIG. 50.—Arrangement for producing electric oscillations. *SP*. Induction coil. *B*. Spark balls. *C*. Condenser. *MM*. Metal plates of condenser.

The small air gap between the spark balls remains a perfect insulator until the electron pressure has reached a certain voltage, depending on the distance between the balls. At this point electrons burst out of the negative ball, and by their impact they ionise the air molecules or liberate from them electrons by

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collision. The ionised air is a conductor of electricity, and hence at that instant the balls are as good as put in contact and the discharge circuit is completed. The electric oscillations of the condenser electrons then take place as already described, and as these oscillations die gradually away the air between the spark balls resumes its insulating power. The process then repeats itself and we have a series of groups of die-away oscillations called trains of damped oscillations.

In a later section we shall describe the manner in which oscillations called undamped or continuous oscillations can be created.

To give some idea of what these units mean we can say that the electrical capacity of a Leyden jar, formed with a glass bottle or jar of about a pint in capacity, might be somewhere about one-thousandth of a microfarad. The electrical capacity of the whole earth considered as a spherical conductor insulated in space is only about 800 microfarads. The capacity of a mile of submarine cable is about one-third of a microfarad.

If we make our measurements in these units the formula for the frequency of oscillation in a condenser circuit takes the following form :—

$$n\left(\begin{matrix}oscillations\\per\ second\end{matrix}\right) = \frac{5{,}000}{\sqrt{C\left(\begin{matrix}in\\microfarads\end{matrix}\right) \times L\left(\begin{matrix}in\\millihenrys\end{matrix}\right)}}$$

Thus, for instance, if we had a charged Leyden jar having a capacity of 1/500th of a microfarad and

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discharged it through a yard or two of connecting wire, which might have an inductance, say, of 1/500th millihenry, the frequency by the above formula would be $2\frac{1}{2}$ millions. This means that the time of one complete oscillation current would be four ten-millionths of a second.

A circuit of this kind is called an oscillatory circuit, and every such circuit has a natural time of vibration in which its electric charge oscillates when disturbed, just as every pendulum of a given length has its own natural time of vibration if it is set swinging.

30. Electric Radiation from Oscillatory Circuits.

It has already been explained that an electromagnetic wave is created when an electron suddenly changes its speed or is started or stopped in motion.

In the discharge wire of an oscillatory circuit, and also in the dielectric or insulator of the condenser, electrons are dancing backwards and forwards with great rapidity, whilst the oscillations are taking place. Hence an oscillatory current must create electric waves which may be regarded as vibrations propagated outwards along the lines of electric force proceeding from electrons.

If, however, we consider the kind of circuit just described in which the metal plates of the condenser are very near to each other, and only separated by a thin sheet of dielectric, we shall see that when one

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plate has its largest charge of extra electrons and the other plate its greatest deficit, which happens twice at each complete oscillation, then, owing to the proximity of the plates, the lines of force which start from electrons nearly all terminate within a short distance upon positive ions or atoms which have lost an electron. Very few of these electrolines stretch far out into space. Hence, when vibrations are started along these electrolines by the sudden movements of the electrons, very few of these vibrations are propagated entirely away from the condenser. In other words, the arrangement radiates badly because it does not get rid of much of the stored energy in the form of electric vibrations or waves propagated along electrolines, which extend far into external space.

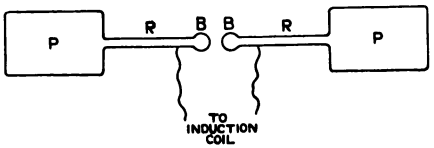


FIG. 51.—A Hertz oscillator or radiator. *PP*. Metal plates. *RR*. Metal rods. *BB*. Spark balls.

The oscillatory circuit above described is sometimes called a closed or nearly closed oscillatory circuit and it is a poor electric radiator.

In 1887, H. Hertz invented a type of oscillator which has very great radiative power. Instead of placing the condenser plates near together he placed them as far apart as possible by attaching them to the outer ends of two metal rods placed in line

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with each other, their inner ends being provided with spark balls in proximity to each other (see Fig. 51).

When these rods are connected to the terminals of an induction coil or electrical machine in operation, the plates are charged; one has an excess of free electrons, and is therefore negatively charged, and the other has a deficit, and is positively charged. When the electric pressure reaches a value determined by the length of the air gap between the balls, the conductivity of the air breaks down, it is ionised, a spark passes, and electric oscillations take place, that is, free electrons vibrate backwards and forwards in the wire or rods.

If we consider the distribution of the lines of electric force (electrolines) proceeding from the electrons in the negatively charged side of the oscillator rods before the spark discharge takes place, it will be seen that a large proportion of these lines must stretch far out into space on all sides of the oscillator rods, starting from the rods in a direction nearly at right angles to them (see Fig. 52).

When the spark discharge takes place the electrons crowded together in the supercharged (negative) rod begin to move suddenly towards the other deficiently charged rod so as to equalise the electron distribution or pressure.

This sudden motion of the electrons produces a "kink" or bend or loop on the electrolines on

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account of the inertia of the latter as already explained in a previous section. The kinks on all similarly directed electrolines run together into a transverse loop of electric force (see Fig. 52) which flies outwards in the direction of the electrolines.

The lateral motion of a line of electric force produces a magnetic force which is at right angles to the direction of the line of electric force and to that of its motion. Hence the moving loop of electric force is accompanied by moving loops or lines of magnetic force; the end on view of these last named lines are represented by the *dots* in the diagram in Fig. 52.

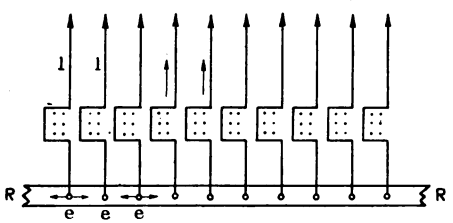


FIG. 52.—Vibrations being propagated along electrolines (*l*) proceeding from electrons (*e*) in oscillation.

This combination of lines of electric force and lines of magnetic force at right angles, both sets moving at right angles or perpendicularly to their own direction, is called an *electric wave*.

This wave moves with a velocity of 300,000 kilometres per second in empty space or in air, which is the same as the velocity of light. Otherwise stated, its velocity is 1,000 million feet per second.

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Twenty-two years before Hertz began his experiments, Maxwell, in 1865, had theoretically arrived at the conclusion that electric and magnetic forces were propagated through space, not instantly, but with the velocity of light, and had predicted the possible existence of electromagnetic waves, and had given reasons for the opinion that visible light and, therefore, also radiant heat consist of electromagnetic waves of very short wavelength.

Maxwell had not, however, described any mode in which these long electromagnetic waves could be created or detected. The late Professor G. F. Fitzgerald suggested that Maxwell's electromagnetic waves might be created by the oscillatory discharge of a Leyden jar. He had also theoretically investigated the production of electromagnetic radiation by a high frequency alternating electric current in a closed loop of wire.

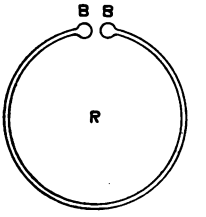


FIG. 53.—A Hertz resonator ring.

The late Professor D. E. Hughes had undoubtedly succeeded experimentally in generating Maxwell's electric waves, and what was more important he had empirically discovered a way of detecting them without clearly understanding what he was doing. Hughes' original apparatus is now exhibited in the Science and Art Museum at South Kensington, London.

Hertz invented a simple but not very sensitive

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method of detecting these Maxwell waves by using a circle of stiff wire, which was interrupted in one place by a small pair of spark balls (see Fig. 53), forming the earliest type of what is now called a *frame aerial*, Hertz used this "resonator," as he called it, in the following manner. He placed at one station his open circuit oscillator (see Fig. 51) with its rods in a horizontal position. When this

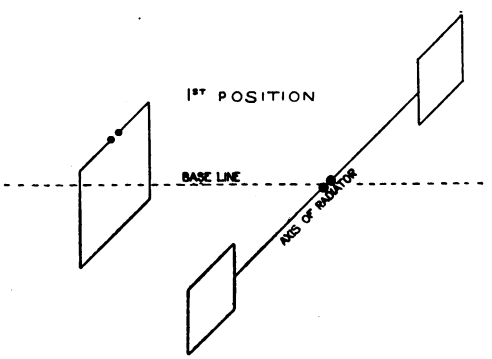
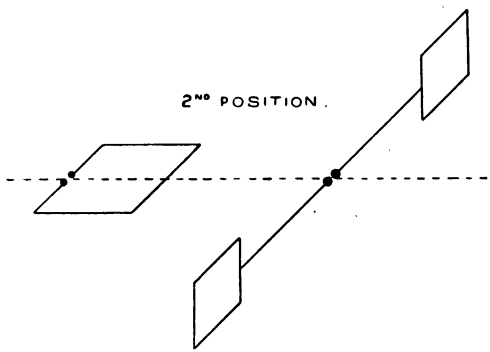


FIG. 54.—(*a*) Sparks are seen at resonator balls when the oscillator is in action.

oscillator was in action it sent out electromagnetic waves in which the electric force was in a horizontal direction and on the axial line nearly parallel to the oscillator rods. Also the motion of these created magnetic force disposed in a vertical direction and in the same plane as the electric force. The resonator ring was then placed at a certain distance away from the oscillator with its plane vertical and its spark gap turned so that the line joining the

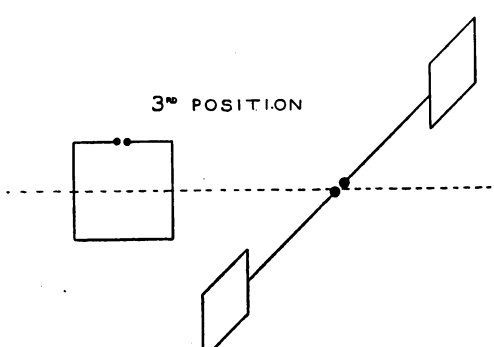
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resonator spark balls was parallel to the line joining the spark balls of the oscillator (see Fig. 54).



(*b*) No sparks seen at resonator balls when oscillator is in operation.

Under these conditions small sparks are seen at the receiver balls. These are due to the fact that



(*c*) No sparks seen at resonator balls when oscillator is in operation.

the lines of magnetic force of the electric wave sent out by the oscillator cut through the two sides of

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the resonator, but do not cut them simultaneously. The result is to produce in the circuit of the ring two opposite but unequal electromotive forces which create a current in the ring, and hence a spark at the resonator balls.

This effect needs a little further explanation, and we must therefore explain on the electron hypothesis the nature of the physical operations which produce the induction, as it is called, of electric currents.

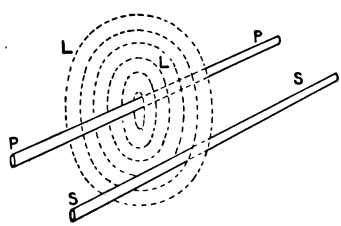


FIG. 55.—A diagram showing the manner in which expanding lines of magnetic force round a primary circuit *PP* cut a secondary circuit *SS*.

Faraday's greatest experimental achievement was his discovery in the autumn days of 1831 that a magnet moved near to a conducting circuit in such manner that the lines of magnetic force proceeding from the poles of the magnet "cut across" the wire circuit.

It is necessary to interpret this effect in terms of the electron theory. Consider two straight copper wires stretched parallel to each other (see Fig. 55). We have seen that an electric current consists in a procession of free electrons in the wire, which though agitated by an irregular motion, yet all struggle forwards in one direction. We have also pointed out that when an electron moves it creates circular lines of magnetic force which lie

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in planes perpendicular to its line of motion. Again it has been mentioned that these lines of force do not spring into existence suddenly at all distances from the electron, but are gradually propagated outwards with the velocity of light just as the circular ripples produced on a pond by casting into it a stone gradually expand outwards in circles of ever-increasing size (see Fig. 55).

Consider then the case when we start a direct current in a wire *PP*. The electrons in one of the wires then begin to drift forward. The circular lines of magnetic force *LL*, which are thereby generated, grow out from the primary wire *PP*, enlarging gradually in size. These lines therefore in time " cut across " the other parallel wire *SS*.

In a previous section it has been pointed out that when a line of magnetic force moves parallel to itself it creates an electric force which is in a direction at right angles to the lines of magnetic force and to the direction of motion of the latter.

We can memorise the relative directions by holding the forefinger, the thumb and the middle finger of the right hand in directions mutually at right angles (see Fig. 56). Let the direction in which the forefinger points be the direction of the line of magnetic force, that means the direction in which the pole of a magnet which points to the earth's North Pole would be moved along it.

Let the direction of the thumb represent the direction in which the aforesaid line of magnetic

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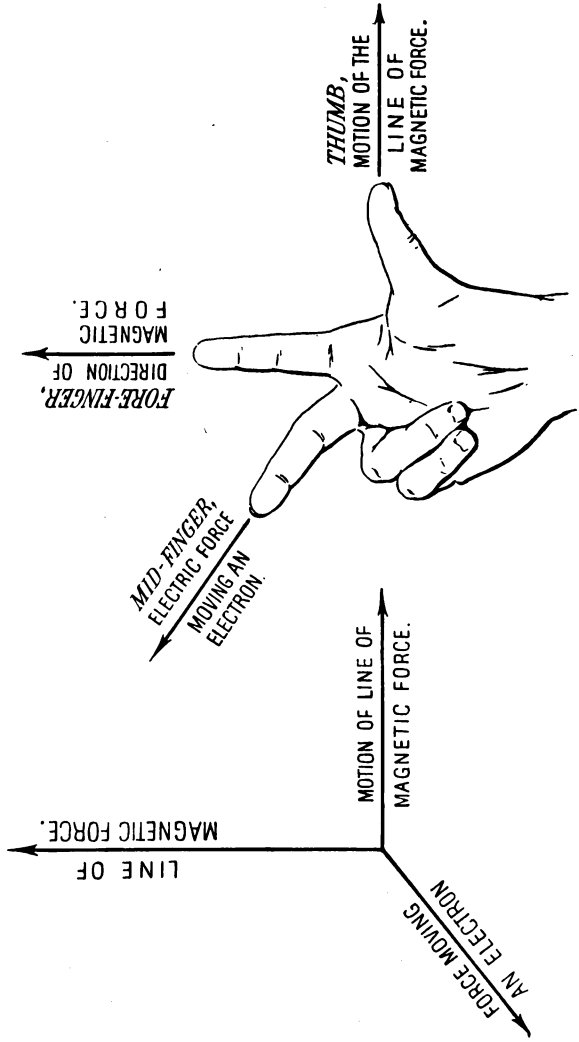

THUMB, MOTION OF THE LINE OF MAGNETIC FORCE.
FORE-FINGER, DIRECTION OF MAGNETIC FORCE.
MID-FINGER, ELECTRIC FORCE MOVING AN ELECTRON.
RIGHT HAND.
MOTION OF LINE OF MAGNETIC FORCE.
LINE OF MAGNETIC FORCE.
FORCE MOVING AN ELECTRON

FIG. 56.—The Fleming right hand rule, connecting electric force, direction of flow of current and direction of motion lines of magnetic force.

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force is moving transversely to its own direction. Then the direction in which the middle finger points will be the direction in which a negative electron, in a conductor, across which this line of magnetic force moves, will be urged by the electric force created by the motion of the line of magnetic force.

Since the secondary wire contains free electrons, the result is that as the lines of magnetic force generated by the motion of the electrons in the primary wire " cut across " the secondary wire, a momentary electric force will be created in it, which will move the free electrons in the secondary wire in the *opposite* direction to the movement of those in the primary wire. This is called an induced secondary current at " make." It only lasts for a short time, namely, whilst the circular expanding lines of magnetic force are taking up their permanent positions in space.

Suppose then that the current in the primary wire is stopped or that the drifting electrons in it are brought to rest. This implies that the magnetic field round the wire vanishes. It does not, however, vanish at all distances at the same instant, but the circular embracing lines of magnetic force are, so to speak, sucked back into the wire. In so doing it will be evident that some of them again " cut across" the secondary circuit, but in an opposite direction to that in their outward course.

It will be clear then from the above explanation that the result of this contraction is to create a

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momentary electric force which drives the free electrons in the secondary wire in the *same* direction as that of the drift motion of the electrons in the primary wire. This is called the induced current at " break " of primary current.

It will be seen then that if the primary circuit is traversed by an alternating electric current, that is if the free electrons in the primary wire surge backwards and forwards like the ebb and flow of the tide in the mouth of a tidal river, the result will be to produce a similar alternating current in the secondary wire or surging motion of its free electrons which keeps in step with the primary current, but is always in an opposite direction as regards flow.

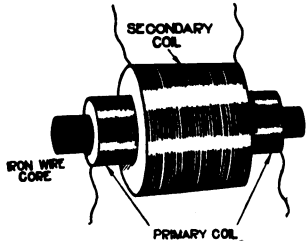


FIG. 57.—An induction coil consisting of two insulated wires wound round a bundle of fine iron wires as a core.

It is not necessary that the two wires should be straight ; they may be both coiled in spiral fashion round a rod or tube of wood or insulating material, only then each wire must be covered with silk, cotton or enamel, to insulate the turns from each other (see Fig. 57).

An arrangement of this kind is called an *Induction Coil* or *Transformer*.

When the alternating current is a low frequency current, viz., about 50 to 200 or so reversals of

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current per second, we can increase the effect by inserting in the tube on which the wires are coiled a bundle of fine iron wires called an iron core. In the case of high frequency current no iron core of the above kind is of advantage.

The induction of electric currents by moving

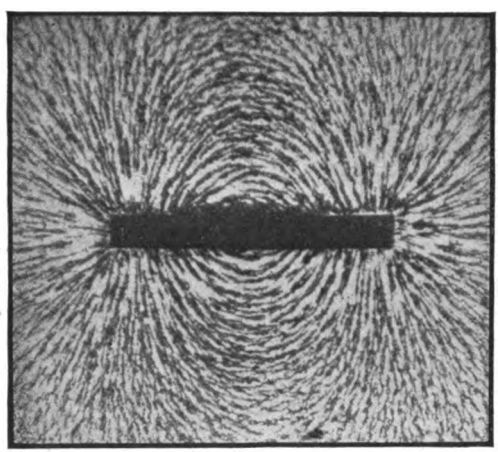


FIG. 58.—Lines of magnetic force round a bar magnet delineated by sprinkling iron filings on a sheet of paper laid over the magnet.

magnets proceeds from similar causes. A permanent magnet, whether bar or horseshoe, carries about with it a field of magnetic force, the direction of the lines of which may be rendered evident in the well known manner by sprinkling iron filings upon a sheet of paper laid over the magnet (see Fig. 58).

If then the magnet is moved in any manner so that its lines of force "cut across" a conducting

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wire, the free electrons in the latter are urged in one direction along the wire for the same reasons as explained in the case of the expanding magnetic field of a primary wire.

This fact is the starting point for the construction of all forms of dynamo electric machines, in which a current is generated by moving a coil of wire in a magnetic field of force.

The ordinary spark induction coil, so much used in Röntgen or X-ray work, consists of a bundle of fine iron wires which is wound over with a number of coils of cotton-covered copper wire through which passes the current from a battery which is rapidly interrupted or started and stopped by means of an appliance called a "break." Over this primary coil is wound in sections an immense length of very fine silk-covered copper wire called the secondary coil. When the primary coil is traversed by the primary current the lines of magnetic force due to it are linked with the secondary circuit or pass through it. When the primary current is suddenly stopped these lines contract or shrink up again into the primary circuit. In so doing they "cut through" the secondary circuit and create in it a very high electromagnetic force, urging the free electrons in the secondary circuit violently in one direction. So much so that they burst forth at one end of the secondary circuit and create a spark discharge.

The electric force, or force moving the free

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electrons in the conducting wire, is proportional to the product of the magnetic force H of the moving lines of magnetic force and to the velocity v if these lines resolved perpendicularly to the wire.

If the wire has a length l centimetres then the electromotive force produced by these lines cutting or crossing the wire is proportional to the triple product Hvl.

It does not matter whether the copper wire moves transversely to the field at rest, or whether the lines of magnetic force themselves move, as in the case of an electric wave, so as to cut across a stationary conducting wire. In both cases we have an induced electromotive force created.

We can now return to the consideration of the Hertz oscillator and its corresponding receiving circuit.

It has been explained that when the free electrons in the oscillator rods dance backwards and forwards with great rapidity, the result is to propagate outwards along the electrolines proceeding from the free electrons in them "kinks" or vibrations, which may be conceived to travel along the electrolines just as a "kink" or wave travels along a stretched cord fixed at one end when a sudden jerk is given at the other end.

The "kinks" produced simultaneously on a number of electrolines which are in the same direction run together into a travelling loop of electric force which moves with the speed of light

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in the direction of the electrolines and is accompanied by lines of magnetic force, the directions of which are perpendicular to the electrolines and to the direction of motion of the latter (see Fig. 52).

Suppose next we set up at any distant place another oscillator exactly like the transmitting oscillator comprising two plates at the outer extremities of two rods placed in line and with a gap in the middle which can be bridged over by some form of conductor. Let this receiving circuit, as it is called, have its rods placed parallel to the rods of the transmitting oscillator. Being of the same form as the transmitter, this receiving circuit has the same natural time period of oscillation. In other words, it is " in tune " with the transmitter.

Hence, as the lines of magnetic force in the electric wave passing over it cut across the rods they will create in them an alternating electromotive force. If the receiving circuit is not in tune with the transmitter, the latter would produce very little effect in creating a current in the former. If, however, it is in tune, the repeated action of the incident waves will soon create an alternating current in the receiver.

The action is closely analogous to the effect of jumping upon a springy plank supported at the two ends like a bridge. The plank has mass and elastic resistance to bending. If a boy stands in the middle of the plank his weight causes it to bend slightly. The plank has, however, a natural time

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of oscillation. If the boy jumps up and down, but not in time with the natural period of oscillation of the plank, he will not produce much effect in increasing the deflection. If, however, he times his jumps so as to agree with the natural time period of flexural vibration of the plank, he will soon find that the bending of the plank at each jump becomes so large that it will probably be in danger of breaking. It is for this reason that a regiment of soldiers are generally ordered to "break step" on crossing a suspension bridge, because if it should so happen that the time period of their marching feet should agree with the natural period of flexural oscillation of the bridge, the safety of the structure might be endangered.

For the same reason we can set in strong oscillation a pendulum consisting of a massive bob suspended by a string by means of little puffs of air or feeble blows with a feather, provided we administer these impulses at intervals of time exactly equal to the natural time period of oscillation of the pendulum. This fact in its widest form covers the principle of the *resonance* of two vibrating bodies, and is of very great importance in connection with wireless telegraphy and telephony.

We have seen that when two circuits are adjacent to each other an alternating current in one circuit will induce an alternating current in the other circuit. Suppose these two circuits each consist of a condenser of a certain capacity C in series with a

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wire having a certain inductance L. The natural time period of the circuit is then, as we have shown, proportional to the square root of the product of the capacity of the condenser and the inductance of the wire or to $\sqrt{CL}$.

This last is called the *oscillation constant* of the circuit.

If then the two circuits have equal oscillation constants, even though in one the capacity is large and the inductance small, whereas in the other the reverse is the case, these circuits will be in tune with each other, and if placed in proximity free oscillations created in one circuit will induce strong oscillations of equal frequency in the other circuit. It should be noted, however, that when a pendulum or other system capable of vibration receives a single blow or impulse it will, if then left to itself, vibrate in its own natural time period. So in the case of an electric oscillatory circuit, a single strong electromotive impulse due to an electric wave falling upon a properly-tuned receiving circuit will set it in prolonged oscillation provided that this receiving set is not too good a radiator.

Thus, in the case of Hertz's original experiments, he used the transmitting rod oscillator above described, and a nearly closed receiving circuit made of a circle of wire with a small spark gap in it.

This rod oscillator is a very good radiator, and sends out all its accumulated electric energy in one or two vibrations at most.

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On the other hand, the closed receiving circuit is a very poor radiator, yet when struck by the electric waves from the transmitter it is set in prolonged oscillation, and there may even be 500 oscillations of current in it before they completely die away.

31. Detection of Electric Waves.

It will be clear, then, that to detect electric waves passing through space we have to place at that point an oscillatory circuit, which is generally of the open circuit or rod type, which must have the capacity of its two parts, with respect to each other and the inductance of its rod or wire, so adjusted that the natural period of oscillation of the oscillator agrees with that of the wave to be detected. Next, the oscillator must be placed with its rods parallel to the direction of the electric force in the wave. If it is a nearly closed or loop receiving circuit, its plane must be coincident with that in which the electric force component of the wave lies.

The incident electric waves then produce in this receiving circuit a feeble oscillatory current of the same type as that in the transmitting circuit.

To complete the detection we have furthermore to associate the receiving circuit with some device called a *detector*, which is in effect a very sensitive kind of ammeter or voltmeter for detecting high frequency electric currents, and enables us to detect

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the presence in the receiving circuit of a very feeble electric oscillation.

There are only two types of such detector at present much used, viz., the crystal detector and the thermionic valve detector, but we shall mention first the coherer, as this form of detector enables us to show with great ease many of the properties of electric waves which are illustrative of wave phenomena in general.

It had been known for a long period of time that metallic filings formed a conductor of a peculiar kind, and that a glass tube loosely filled with such metallic filings had a conductivity which varied in a very irregular manner.

Professor E. Branly, of Paris, drew attention in 1890 to the fact that an electric spark taking place near such a tube of loose metallic filings caused a sudden increase in its electric conductivity. The same thing appears to have been noticed previously in 1887 or 1888, by Professor D. E. Hughes, the inventor of the microphone.

Sir Oliver Lodge observed in 1893 the improved conductivity a loose or microphonic metallic contact produced when an electric oscillation passed through the contact, and named the device a *coherer*.

Without entering into historical developments, we may say that the coherer, in the form given to it by Marconi, consists of a very minute quantity of metal filings, preferably nickel, with a small

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percentage of silver, which is contained between two silver plugs included in a glass tube.

The tube is exhausted of its air. The plugs are connected to two platinum wires sealed through the glass.

For certain laboratory and experimental purposes the author has used with advantage another form made as follows: A small ebonite box, like a little pill-box, has two nickel or silver wires passed through holes in the sides so that the wires are not quite in line (see Fig. 59). The wires where they pass through the box must be parallel to each other and about two millimetres, or not more than 1/12th of an inch apart. They must otherwise rest on the flat bottom of the box. A very small quantity of fine clean nickel filings is then laid between them, and this quantity has to be adjusted until the greatest sensitiveness is obtained. The length of wire which projects beyond the box on each side is about three inches. A little stopper of ebonite is provided to close the top of the box. The two wires and the filings connecting them are joined in series with a single

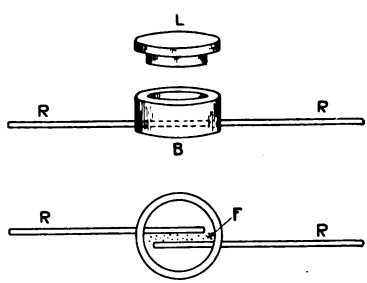


FIG. 59.—A type of coherer used by the author in Hertzian wave experiments. *RR*. Metal wires. *B*. Ebonite box. *F*. Nickel filings between the wires in the box.

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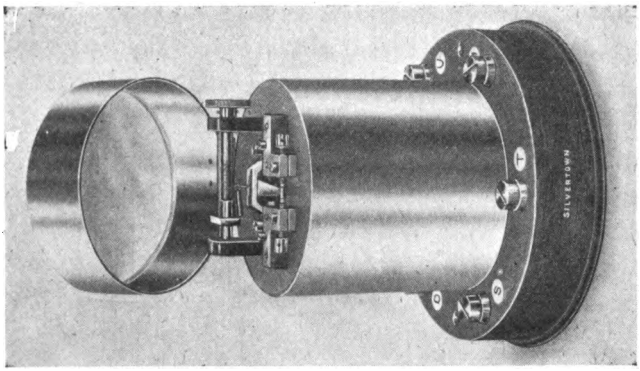
dry voltaic cell, and with the wire circuit of a device called a *relay*.

A relay consists of a pair of soft or pure iron bars round which are coiled many convolutions of fine silk-covered copper wire, through which the electric current from the battery cell can be sent. The iron then becomes a magnet, and the arrangement is called a electromagnet. When the iron bars are thus magnetised, which can be done sufficiently with a very feeble electric current, the poles of the electromagnets are caused to attract a pivoted piece of soft iron (see Fig. 60), called an armature, and pull it over against a metal stud, which effects a contact and completes another electric circuit which contains a more powerful battery of many cells and some instruments such as an incandescent lamp, an electric bell, or a printing telegraph instrument, which can give a visible, audible or legible signal. The relay is therefore a device by which the starting or stopping of a very feeble electric current can cause another very much stronger electric current to be also started or stopped.

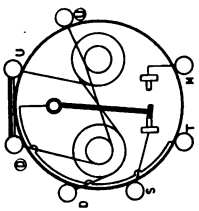
Let us suppose then that we have two metal rods, each a few inches long, placed in line with polished metal balls on their inner ends, with a small spark gap between them, so as to form a Hertzian oscillator.

It is desirable that this oscillator should be contained in a metal box with one end open (see Figs. 61 and 62).

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A telegraph relay.



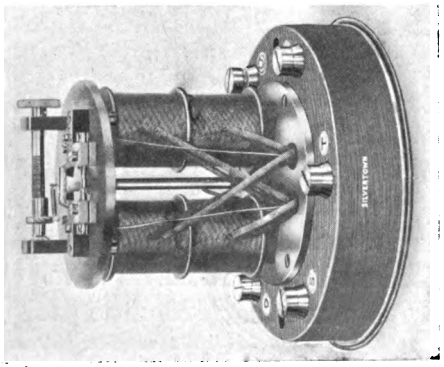


FIG. 60.—A telegraph relay with outer case removed.

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By means of an induction coil or electrical machine electric sparks are created between the balls. This results, as already explained, in the production of electric oscillations in the rods and in radiation of electric waves from them.

The wavelength of the waves radiated is approximately twice the overall length of the two rods. Hence to obtain short Hertzian waves, that is, not more than a few centimetres in wavelength, the

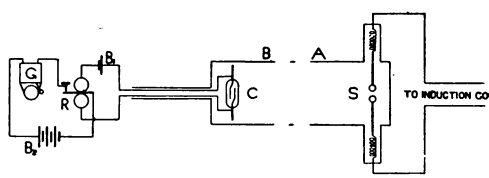


FIG. 61.—Apparatus for experiments with short Hertzian electric waves. *S*. Oscillator rods in open mouth box *A*. *C*. Coherer in box *B*. *R*. Relay. *G*. Electric bell.

spark balls and the rods must not exceed in length half the desired wavelength.

It is necessary to connect these rods to the spark producing appliance, which is generally a small induction coil, through tightly wound up spirals of indiarubber-covered wire, called choking coils. The object of this is to hinder the electric oscillations generated in them from passing back into the induction coil. Another precaution is to have the spark balls highly polished, as this helps to produce that suddenness of the electric discharge which is a necessary condition for creating electric waves.

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The receiving arrangements, comprising the metallic filings, coherer, and the extended wires, are placed in another metal box, open at one end, the two boxes being arranged with open ends facing each other and at a little distance, and the oscillator rods parallel to the collecting wires of the receiver (see Fig. 62).

It is very important that the wires which lead away from the coherer to the relay and voltaic cell and from the relay to the indicating device, whether lamp or bell, should be enclosed in a metal tube, and all joints made tight. The object of this is to prevent the electric waves radiated from the transmitter affecting the coherer otherwise than by entering the open mouth of the receiver box.

To control the emission of waves from the transmitter it is necessary to insert in the primary circuit of the spark-producing coil a switch or key, so that we can create a spark of short duration between the spark balls by closing this switch for an instant.

A train of electric waves having a wavelength of a few inches then emerges from the open mouth of the transmitter box and enters that of the receiver or coherer box. These waves set up electric oscillations in the collecting wires, which causes the metal filings in the box to become highly conductive. The metal particles cling or cohere together. The voltaic cell in series then sends a current through them and through the relay, which in turn operates the detecting device and lights up the indicating

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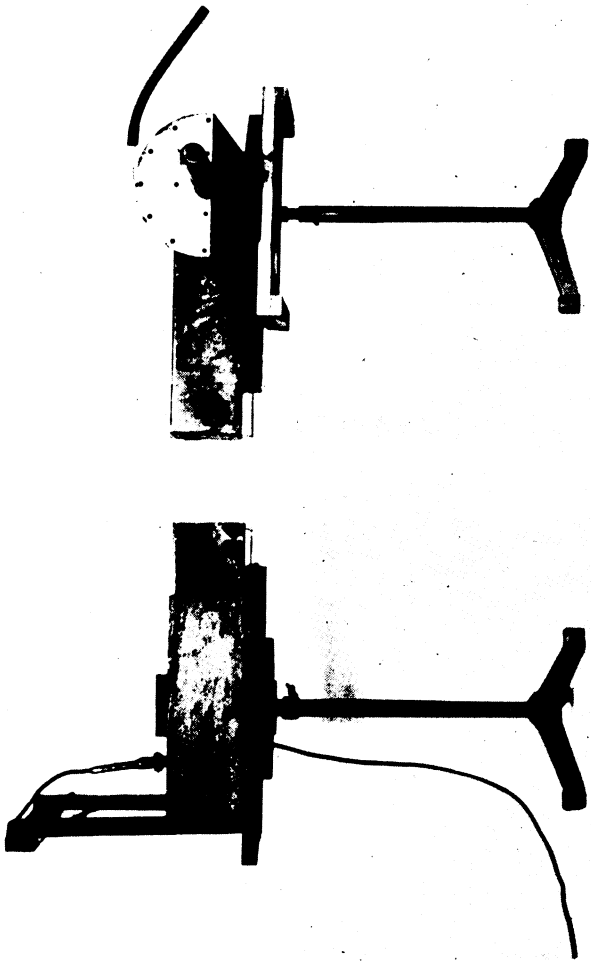


FIG. 62.—General view of the author's apparatus for showing experiments with short electric waves, illustrating their similarity to light waves and the opacity or transparency of various substances.

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lamp or rings the electric bell. This signal then shows that an electric wave has entered the receiving box. If we stop the transmitter spark and give the coherer box a smart tap or blow, this causes the metallic filings to cohere or fall back again into a badly conducting condition, and the indicator lamp then goes out or the bell stops ringing.

Provided with this apparatus we can then demonstrate a number of the interesting properties of electric waves having a wavelength of a few inches.

In the first place if we hold between the transmitter and receiver boxes a sheet of metal, even a sheet of tin foil or silvered paper, we find that the metal is opaque to these waves, and that the receiver is not affected.

The reason is because the electric waves falling on the metal sheet set up in it oscillatory electric currents, and these are exactly in opposite phase; that means moving in opposite directions to the currents in the oscillator rods which generate the waves. These currents in the metal sheet in turn create waves which, however, being in opposite phase, just nullify the effect of the incident waves on the receiver.

All good conductors are therefore opaque to this type of electric wave.

On the other hand, bad conductors are transparent. If we hold a sheet of glass, ebonite, or even a thick plank of dry wood, between the oscilla-

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tor and the detector, these electric waves are found to pass through it quite easily.

They pass also through many folds of dry cloth. If, however, the cloth is made wet, even a wet duster will do, it is found to be opaque to them. For this reason the human body, hand, and head are also opaque, and stop these electric waves on account of the water in the tissues. A number of interesting experiments may be made with flat glass bottles, about 6 inches square and an inch in thickness. It will be found that the empty bottle is quite transparent to these waves. If filled with water it is quite opaque. If filled with paraffin oil, olive oil, turpentine or other insulating liquid, it is found to be transparent.

Methylated spirit is transparent if quite free from water, but the water-adulterated mixture is semi-opaque.

We learn from these experiments that, generally speaking, good conductors are opaque to long electric waves, and good insulators transparent.

This is not the case, strictly speaking, for the very short electric waves which constitute visible light. In the latter case many aqueous solutions of salts called electrolytes, because they can be decomposed by an electric current, are transparent to light, and yet are good conductors. The reason is because in light waves we are dealing with electric displacement currents which are reversed hundreds of billions of times per second, and many substances

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which are good conductors for low frequency currents are not good conductors for extra high frequency currents. Another interesting experiment can be shown with a grid of wire. If we wind copper wire round a wood frame so as to lay a number of parallel wires about half an inch apart across the frame in one direction (see Fig. 63), we find that this grid is opaque to the electric radiation when the frame is held between the receiver and transmitter with the grid wires parallel to the oscillator rods, but is transparent when it is turned into a position such that the wires are perpendicular to the oscillator rods, the plane of the frame in both cases being perpendicular to the line joining the spark balls and the coherer.

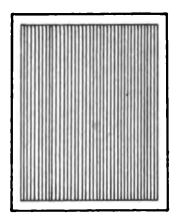


FIG. 63.—A grid formed by winding wires round a wooden frame.

The reason is because in the former case electric currents are set up by the electric waves in the grid wires, and in the latter case they are not.

The waves emitted are therefore said to be plane polarised; that means the vibrations are confined to one particular plane. This is the case with light waves when they have been transmitted through certain crystals such as tourmaline.

We can next exhibit the reflection and refraction of these invisible electric waves, and show that they behave like waves of light.

If we turn the transmitter and receiver boxes with

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their open ends in nearly the same direction, but placed not quite near each other, it is possible to find positions in which the emitted waves do not enter the receiver box and affect the coherer. If, however, we hold a sheet of metal we can reflect the invisible electric beam into the mouth of the receiver box and so affect the coherer.

Moreover, we can do the same thing with a wet duster, and also with the grid of wires, provided we

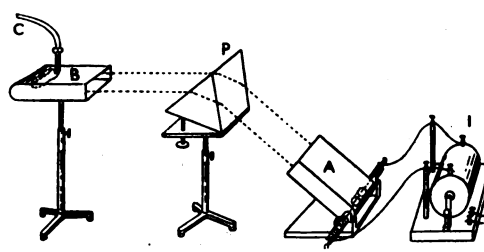


FIG. 64.—An experiment with the apparatus shown in Fig. 62 to illustrate the refraction of short electric waves by a paraffin prism.

hold the grid in such a position that its wires lie in the same plane as the rods of the oscillator.

We shall see later on in speaking of wireless telephony that we can in this manner construct reflectors for electric waves which are not very cumbersome or costly, and especially do not offer much surface to wind.

We can also refract or bend the direction of these waves by means of prisms made of paraffin wax (see Fig. 64).

Again it is possible to produce, as Hertz did, interference effects and to cause two sets of waves to

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augment or to destroy each other just as in the case with waves on water or waves in air.

In short, we can exhibit with this invisible electric radiation similar phenomena to those with which we are so familiar in the case of light, viz., opacity, transparency, reflections, refraction, polarisation, and interference. Great experimentalists, following Hertz's initiative, have therefore built up a body of irrefutable proof that in this invisible electric radiation of long wavelength we are dealing with an agency identical in nature with light, except that it cannot affect our eyes but can only influence certain artificial eyes called aerials and detectors.

This is perhaps the best place to mention the range of these known and also of the unknown wavelengths which are comprised by this electric radiation. It will be convenient to adopt a term from the science of music and call an *octave* of radiation all those waves which are included between a certain particular wavelength and a wavelength of exactly double or else half that length.

We may, then, compare the electric waves of different frequency, extending over a great range, with the keyboard of some large organ, in which each key corresponds to a different wavelength. In the case of an organ a compass of eight or nine octaves includes all the range of musical sounds, but in the case of electric waves we are acquainted with wavelengths extending over nearly 50 octaves, ranging from the longest æthereal billows of 20,000 metres in

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wavelength down to the tiny ripples of less than 1 Angström unit in wavelength, which constitute a certain class of X-ray.

Beginning, then, with the longest electric waves, we can say that the range of wavelength of waves used in wireless telegraphy and telephony extend from 20,000 metres to 10 metres, or, say, over 11 octaves of wireless waves. Then beneath these we have the Hertzian waves, which range from about 10 metres to 5 centimetres in wavelength, or, again, about 11 octaves.

Beneath these we have a range of electric waves from about 5 centimetres in wavelength to 0·3 millimetres, or about 8 octaves of radiation, which has not yet been created, and are therefore unknown.

Again below these, we find the dark heat-waves stretching from 300 microns (μ) or $\frac{1}{3}$ of a millimetre in wavelength to about 0·8μ or 8,000 Angström units (A.U.). These 7 or 8 octaves of radiation can make themselves evident by their heating action on sensitive thermometers, but do not affect our eyes as light. Extending in wavelength merely 1 octave from 0·8μ to 0·4μ in wavelength, we have that small range of electric waves which can affect the human eye as light. Beyond the violet rays there is a range of 3 or 4 octaves or more of invisible light, which cannot affect our eyes but can impress a photographic plate, and produce other effects. These are called the ultra-violet waves, and their

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wavelengths extend from about 4,000 A.U. down to perhaps 500 A.U. or less.

Below these there is another gap of unknown or unproduced wavelengths, and then we come to the region of X-rays and Y-rays, which are electric waves with wavelength of the order of 1 A.U. or less.

We are therefore acquainted with the properties of a vast gamut of electric waves with, however, two gaps in it of unknown waves, but covering on the whole about 50 octaves of radiation. For all we know, there may be in the economy of Nature waves of still greater or still less wavelength as yet unproduced.

32. Production and Detection of Electric Waves of Great Wavelength.

Our next step must be to explain the manner in which electric waves of much longer wavelength than those employed in the above experiments can be created and detected. Especially is it necessary to describe the method of generating the type of electric wave employed in wireless telephony.

It will be convenient to begin with a description and explanation of an instrument called a thermionic valve; because this is used not only to create but to detect these electric waves of great wavelength.

It has been mentioned already in speaking of the free electrons in conducting materials that these atoms of electricity are in constant irregular motion

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in the inter-atomic spaces. Part at any rate of the sensible heat contained in any substance, which gives it what we call its temperature, is due to the energy of motion of these free electrons.

According to a certain theory called the theory of equipartition of energy, these free electrons should have the same average kinetic energy as gas atoms would have at the same temperature. We have seen that the root mean square (R.M.S.) value of the velocity of molecules of oxygen gas is nearly 461 metres per second, and since the atom of oxygen is 16 times heavier than the atom of hydrogen, the R.M.S. velocity of hydrogen molecules is $\sqrt{16} \times 461 = 1844$ metres per second. But a negative electron has a mass of about 1/1700th of that of a hydrogen atom. Hence the R.M.S. velocity of the free electrons in a conductor should be $\sqrt{1700} \times 1844 = 41 \times 1844 = 75604$ metres per second, or nearly 47 miles per second.

It should be stated, however, that there are some arguments against the application of the principle of equipartition of energy in the case of atoms of matter and electrons. Hence, this statement as to the velocity of the free electrons must be held as liable to correction.

If the temperature of the conductor is raised this electronic velocity will be increased, being nearly proportional to the square root of the absolute temperature; that is, the temperature reckoned from $-273°$ Centigrade. If then the temperature

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is very high, the velocity of some of the free electrons may become so great that those near the surface of the material are flung off from it.

This, indeed, is what happens when a wire, say, of tungsten is heated to a bright incandescence in a high vacuum, as in the case of the filament of an incandescent electric lamp. It must be remembered however, that every electron which escapes leaves behind it a chemical atom deprived of an electron, and therefore having a positive electric charge of equal amount. Hence, unless we supply from some source electrons equal to those that escape, the metal, if insulated, would soon acquire such a high positive potential as to hold back more electrons from escaping. This emission of electrons, due to high temperature, is called *thermionic emission.*

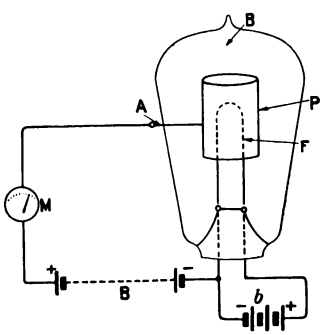


FIG. 65.—A Fleming oscillation valve.

In order that it may take place continuously, we have to surround the incandescent metal with a metal enclosure and to connect the positive terminal of a battery to this sheath or plate, and the negative pole to the hot filament (see Fig. 65).

The arrangement then that is necessary is to construct an ordinary high vacuum incandescent

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electric lamp, having a straight or loop filament *F*, preferably made of drawn tungsten wire, because that material has a very high melting point, and will bear heating to 2,000° C. or 2,500° C. without risk of fusion (see Fig. 61).

Around this filament, but not touching it, is a metal cylinder *P*, made of sheet nickel, which is fastened to a platinum wire *A*, sealed airtight, through the glass bulb. With such an appliance it is very easy to show that an incandescent metal filament in a vacuum is giving off negative electricity by the following experiment (see Fig. 65).

Provide a gold leaf electroscope, consisting of a pair of gold leaf slips contained in a glass bell jar. Connect the terminal of this with the metal cylinder of a valve. Give to the gold leaves and metal cylinder a charge of negative electricity by means of an ebonite rod, rubbed with flannel. If the filament of the valve is not incandescent the gold leaves should remain diverged, that is, the system should retain an electric charge of negative electrons.

If then we make the filament incandescent by passing an electric current through it, we shall find that the negative charge is still retained by the cylinder and gold leaves.

If, however, we give to them a charge of positive electricity by means of a warm glass rod rubbed with silk, the filament being cold or not incandescent, we shall find that the system still retains that charge, provided the insulation is good. The

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moment that the filament is made incandescent by passing a current through it, the gold leaves of the electroscope collapse, showing that a charge of positive electricity is instantly removed from the cylinder. This can only be due to the emission of negative electrons from the incandescent filament. It is convenient to make the filament of such a length that it is rendered incandescent by the current from a storage battery of two to six cells or, say, 4 to 12 volts.

If then we connect the positive pole of another separate voltaic battery to the terminal of the metal cylinder, technically termed the plate, and the negative pole to the negative terminal of the filament, and if we insert in that circuit an instrument called a milliammeter, for detecting and measuring electric currents, we find a current, that is a stream of electrons moving, inside the bulb from the hot filament to the metal cylinder. This is called the *thermionic current.*

Since the stream can only flow when the cylinder is positively electrified and the filament negatively electrified, because the filament can only emit negative electrons, the device enables us to permit electrons to move in a circuit only in one direction. Hence it was named by the author in 1904, who so used it for the first time, an *oscillation valve*, and it is now commonly called a *thermionic valve.*

The great use of it proved to be to convert high frequency alternating currents of electricity into

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unidirectional or direct currents. If in place of the battery we connect the plate of the valve with the filament through a circuit outside the valve which contains some source of alternating electromotive force or high frequency oscillations, then it will be evident that when the electromotive force is in such a direction as to make the cylinder or plate positive, an electron current will flow from the filament, but when the plate is negative it will keep the electrons from coming out of the filament. Therefore the electron current is always in one direction through this external circuit, or plate circuit as it is called. The high frequency alternating current is then said to be *rectified* by the valve, when used as follows :—

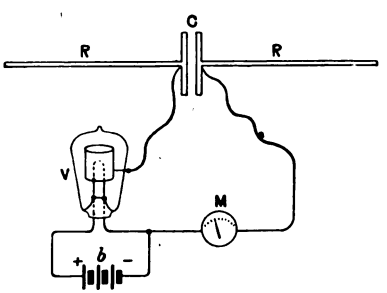


FIG. 66.—*RR.* Rod resonator. *C.* Condenser. *V.* Oscillation valve. *M.* Galvanometer or milliammeter.

Let there be two metal rods placed in line with each other in a region through which electric waves are passing, and let these rods be placed with their lengths parallel to the direction of the electric force in the incident waves, and let their total overall length be adjusted so that it is about $2\frac{1}{4}$ times the wavelength. In other words, let the natural frequency of oscillation of the whole rod be adjusted

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to be equal to the wave frequency (see Fig. 66). Then let these be inserted between the rods, a circuit comprising an oscillation valve as above described, and also a sensitive galvanometer, which is an instrument for detecting a direct electric current. If then an electric wave falls on the receiving rods it will create electric oscillations in them, but the thermionic valve will only allow the currents in one direction to pass and to affect the galvanometer.

If the electric waves are produced by spark discharges in a transmitter, as explained in a previous section, then these waves and the oscillations they produce in the receiving rods come in little groups with intervals of silence. These are called *damped trains of oscillations*. When rectified by a Fleming valve they are then converted into little gushes of electricity, all in one direction, which come at intervals of time equal to the intervals between the spark discharges.

We can then employ as the detecting instrument a telephone receiver, made as explained in the next section.

A telephone does not permit the passage of a high-frequency current through it, but it is caused to emit sound if an interrupted direct current is sent through it, having the frequency of the interruptions between, say, 100 and 10,000. Accordingly, on listening to the telephone receiver when it is joined in series with the plate circuit of a

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thermionic valve, in which a series of damped electric oscillations are being created, we hear a musical sound as long as the groups of oscillations continue. The frequency of this sound is the same as the frequency of the groups of oscillations, that is of the sparks creating them.

An improvement on the original single cylinder or two-electrode valve was effected by the interposition of another cylinder of metal gauze, or a spiral of metal wire between the filament and the cylinder of solid metal. This gauze or spiral cylinder is technically termed a *grid*, and a thermionic valve with a cylinder (plate) and grid is called a three-electrode valve (see Fig. 67).

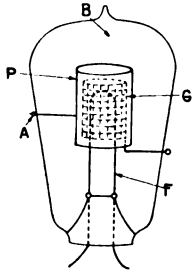


FIG. 67.—A three-electrode thermionic valve.

This triple-electrode valve is remarkable for the astonishing number of ways in which it may be used to detect as well as create electric oscillations. We shall first briefly describe its use as a detector of feeble damped electric oscillations, which come in groups or trains.

For this purpose we connect the negative terminal of a voltaic battery *B*, say, of 40 or 50 cells to one terminal of the filament of a valve, which we shall assume has a filament rendered incandescent by a small separate battery *b* of three cells (see Fig. 68). The latter is called the filament heating battery,

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and the former the plate battery. This last has its positive terminal connected to the cylinder or plate of the valve, and the circuits of a receiving telephone receiver *T* are included in this circuit; the terminals of the telephone are usually also connected to the plates of a small condenser.

In the next place the grid is connected to one terminal of a small condenser *c*, called the grid condenser, and this condenser has its terminals also connected by a very high resistance *l*, called the grid leak, which often consists of a piece of ebonite, on which has been rubbed some plumbago or so-called black lead.

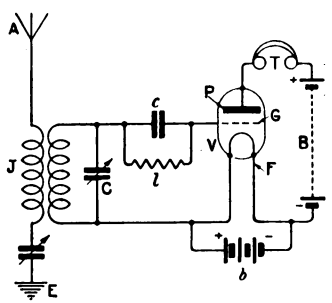


FIG. 68.—One method of using a thermionic valve to detect damped electric oscillations set up in an aerial *A*.

The second terminal of the condenser is connected through one coil of an induction coil with the filament of the valve, the other circuit of this induction coil being included in the circuit in which oscillations are generated by the electric waves to be detected. On the other hand, the filament of the valve and one terminal of the grid condenser can be connected to the receiving aerial wire as shown in Fig. 64.

The operation then is as follows. When electric

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waves fall on the receiving or aerial wire they create in it oscillations, and these in turn charge the receiving condenser in one direction or the opposite, and this causes the grid to be charged with electricity either positive or negative. Again the battery in the plate circuit is causing a stream of electrons to issue from the filament, and these make their way to the plate by passing through the interstices or holes in the grid.

If the grid is negatively electrified, which means if there are negative electrons on it, then, owing to the mutual repulsion of electrons of like kind, these prevent the electrons from the filament from passing through the grid to reach the plate. If, however, the grid becomes positively electrified by the oscillations from the aerial, then the negative electrons from the filament neutralise that positive charge. Hence, the effect of the oscillations in the receiving wires is to cause the plate-current or flow of electrons from the filament to be reduced, and, therefore, to check the current through the telephone. It is then necessary to provide a means by which the negative charge on the grid can be continually removed. This is achieved by the grid leak, which is a very high resistance of several million ohms put across the terminals of the grid condenser. This leak brings the grid back to a neutral condition between the arrival of each group of waves. If then these waves are produced by a spark transmitter of the Hertzian type, the impact

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of each group on the receiving wire causes a sudden decrease in the thermionic current flowing through the telephone, and this, as explained in the next section, causes the telephone to emit a sharp brief sound. If then the groups of waves continue to arrive, these sounds run together into a musical note of the same frequency as the spark of the discharger.

By making these sparks endure for various periods of time, short or long in accordance with a certain code of alphabetic signals, the auditor listening in at the receiving telephone will hear sounds of corresponding duration and can spell out the letters received. In this manner wireless telegraphy on the spark system is accomplished.

Before we can discuss other methods of employing this triple electrode valve for detecting feeble electric oscillations it will be necessary to explain briefly the nature of its *characteristic curve.*

We insert in the external plate circuit of a thermionic valve a battery with negative pole connected to the filament and an instrument called a milliammeter for measuring small electric currents by the deflection of an indicating needle over a divided scale. These currents are conveniently measured in terms of a unit called a milliampere, which is one thousandth part of an ampere, or about one-tenth of the current through an ordinary 200-volt incandescent lamp.

We then make arrangements for giving to the grid

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a positive or negative potential by means of a battery of varying number of cells.

Let us begin with the grid in a neutral or unelectrified condition, viz., at zero potential.

The thermionic current or flow of electrons from the filament has then a certain strength, called the normal strength, when reckoned in milliamperes. This current of negative electrons flows from the filament, through the grid to the plate or cylinder of the valve, and then back through the external circuit and the milliammeters to the filament. We can represent this current by the length of a vertical line *OA* drawn perpendicularly to a horizontal line, on which we mark off lengths proportional to the voltage of the grid (see Fig. 69). If then we make the grid slightly negative, say by 1, 2, 3 volts, etc., we shall find that the plate or thermionic current gradually decreases, and this may be represented by lines of decreasing height drawn at equal intervals of distance to the left of the central normal line. If we make the grid positive, by 1, 2, 3 volts respectively, we find that the plate current increases, but not indefinitely. It reaches soon a maximum value which cannot be exceeded. The plate current is

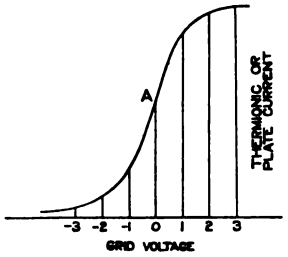


FIG. 69.—A characteristic curve of a three-electrode thermionic valve.

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then said to be *saturated.* If we join the tops of the vertical lines denoting the plate currents we obtain a curve called the plate-grid *characteristic curve* of the valve.

We see, therefore, that if we give the grid a certain positive voltage corresponding to the point at which the curve just begins to bend over, and if we superimpose on this steady voltage an alternating high frequency voltage due to an oscillation, the plate current cannot be much increased when the latter voltage is positive, but it is decreased when the alternating voltage becomes negative.

Hence the superposition of an alternating voltage on the grid then always decreases the plate current and causes a telephone in that circuit to emit a sound which is a musical or continuous sound if the oscillations take place in intermittent groups.

The above methods of using the three-electrode valve as a detector apply only to that class of electric waves in which the waves arrive in little groups or trains with interspaces of silence between the groups ; in other words, to the reception of trains of damped electric waves.

On the other hand, in the great bulk of wireless telegraphy and entirely in wireless telephony, we make use of *continuous waves* (C.W.), which continue without interruption except in so far as they are deliberately interrupted or varied in amplitude to make the signals or speech sounds.

We have then to explain how these continuous

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waves are detected, but must preface this explanation by a description of the manner in which this three-electrode valve can be used to generate electric oscillations, which of late years have become of enormous importance.

It has been explained that if the grid potential varies from positive to negative by removing from or adding to it excess electrons, the plate current or stream of electrons from the filament will also vary, increasing when the grid is positive and decreasing when it is negative.

Hence if we cause the grid to alternate in potential it will make the plate current also fluctuate in such fashion as to be equivalent to the superposition of an alternating current on a direct current.

If we insert in the plate circuit the primary coil of an induction coil, then the terminals of its secondary circuit will provide an alternating voltage which exactly imitates in wave from the alternating potential of the grid, but can be made to have much greater amplitude.

A little thought will make it evident that if we couple back the terminals of the secondary circuit of this induction respectively to the grid and the filament in the right direction, we can cause variations in the plate current to give the grid the proper alternating voltage to sustain those variations in the plate current, so that the apparatus continues to operate to produce high frequency continuous oscillations in the plate circuit.

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We have it in our power to control the frequency of these oscillations by putting condensers C_1, C_2, of suitable capacity across the terminals of the primary and secondary circuits of the induction coil, these circuits being tuned to the same frequency (see Fig. 70).

We are able therefore to use the valve as a generator of undamped oscillations, and it has the property of creating electric oscillations the wave form of which is exactly a simple periodic curve like the sound wave form of a tuning fork or open organ pipe gently blown. Moreover, we can harness together a number of these generator valves so as to employ a battery of them to create very large oscillatory currents of any required frequency and simple or pure wave form.

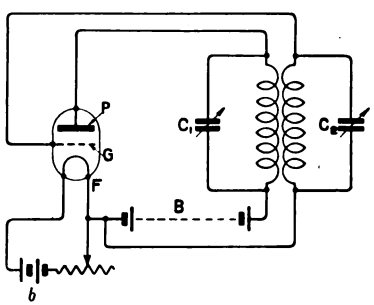


FIG. 70.—Method of using a thermionic valve to create undamped electric oscillations. *P.* Plate of valve. *G.* Grid. *F.* Filament. *B.* Plate battery. *b.* Filament battery.

Generator valves are now made for this purpose, which have glass or silica bulbs about the size of a football, and 50 or 60 of these valves can be arranged on panels to create very large frequency currents.

The illustration, Fig. 71, shows such a large valve panel as is used in the great Marconi Wireless Tele-

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graph station near Carnarvon, on the flank of Snowdon, for world-wide wireless telegraphy.

Another discovery of great practical value in connection with this subject was that if the grid

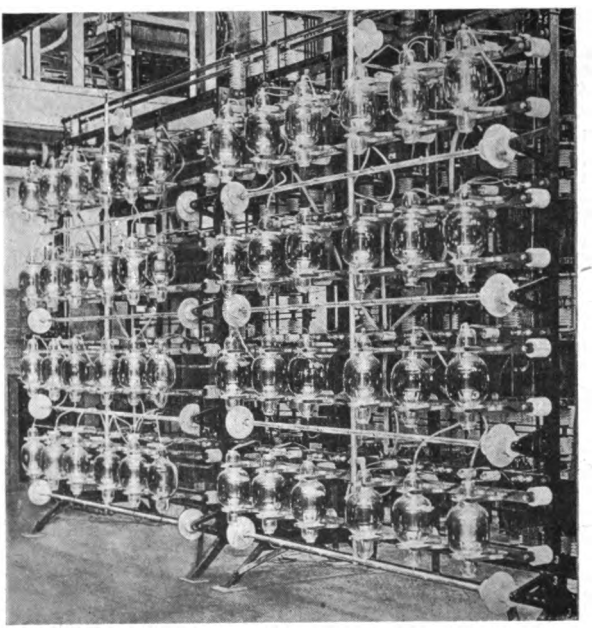


FIG. 71.—Valve transmitting panel at Marconi station, near Carnarvon.

and the plate circuit are coupled together inductively, as above described, but if the primary and secondary circuits in the plate and grid circuits respectively are placed so far apart that they are just, but not quite, on the point of generating self-sustained oscillations, the system becomes very

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sensitive to the effect of any additional electric impulses produced by incident electric waves. The valve is put into a condition in which it is just on the point of self-oscillation, and the effect of the feeblest waves of the frequency for which its circuits are tuned will then be to create oscillations, as long as the waves are arriving. This is called *regenerative coupling*.

We shall discuss its special application in connection with wireless telephony in a later section. Meanwhile it is important to notice that the thermionic valve has an exceedingly valuable use as an *amplifier* of oscillations of high or low frequency.

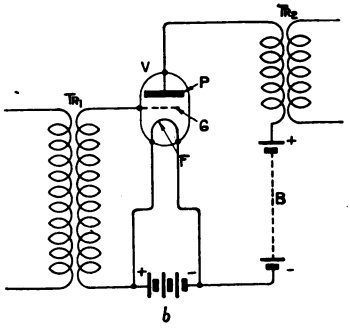


FIG. 72.—A valve amplifier circuit with transformer couplings.

We have pointed out that any variations in the electric potential of the grid are accompanied by corresponding variations in the plate current.

Suppose we insert in the plate circuit one coil of a transformer consisting of two insulated wires, one superimposed on the other, the two wires being wound on one bobbin or tube. In addition, we insert in the plate circuit a battery *B* with its positive pole connected to the plate and its negative pole to the filament (see Fig. 72).

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If now we apply to the grid a feeble alternating electromotive force, this will make the grid alternately positive and negative in potential. This will, as above explained, cause the plate current to fluctuate, and this current passing through the primary coil of the transformer T^2 will create a secondary electromotive force in the adjacent coil which can be made by suitable proportioning of the

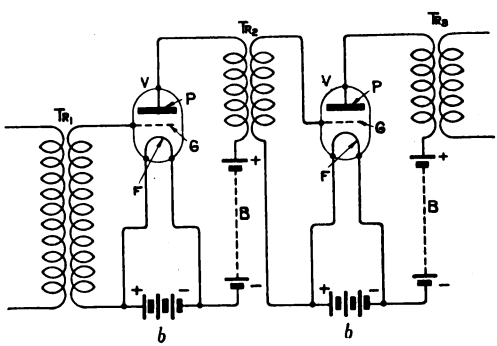


FIG. 73.—Arrangement of two thermionic valves coupled in series by induction coils to amplify electric oscillations.

circuits to have the same frequency, but much greater amplitude than the electromotive force (E.M.F.) applied to the grid. It may, in fact, have an amplitude of 5 or 10 times as great. Thus, if the E.M.G. applied to the grid varies from + 1 volt to — 1 volt, and has, therefore, an R.M.S. value of about 0·707 volt, the E.M.F. on the secondary terminals of the plate transformer may have an R.M.S. value of 5 or 10 times greater.

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The thermionic valve is then said to amplify voltage 5 or 10 times.

It is then obvious that we can apply this amplified E.M.F. to cause fluctuations in the potential of the grid of a second valve similarly equipped with a transformer in its plate circuit, and so amplify a second stage again, say 5 or 10 times. Likewise a third valve may be used, and the result is a magnification of potential by three valves, which is, say, $10 \times 10 \times 10$ that of a single valve (see Fig. 73).

This arrangement of three valves coupled by transformers is called a *three-stage amplifier*. There is hardly any limit to the degree of amplification obtainable in this manner by a number of valves in series.

We can not only amplify the high frequency oscillations called *radio-amplification*, but we can amplify the rectified groups of damped oscillations which have a low frequency, and this is called *audio-amplification*.

The great achievements of modern wireless telegraphy, such as the transmission of radio messages to the Antipodes, and their detection at distances of 10,000 or 12,000 miles, are altogether and entirely due to the invention of the thermionic valve and to the power it has given us of amplifying to any extent extraordinarily feeble electric oscillations produced in aerial receiving wires by electric waves. Before concluding this section a brief

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reference must be made to the use of *crystal rectifiers* as a means of detecting feeble electric oscillations.

It has been found that certain crystals possess the power of conducting electricity better in one direction than in the opposite; that is to say, in certain directions through the crystal there is an unsymmetrical conductivity. This is particularly marked, as first shown by General Dunwoody in the United States, in crystals of carborundum. This material is a highly crystalline compound of carbon and silicon, chemically called a carbide of silicon, and made in an electric furnace by heating to a very high temperature a mixture of powdered coke and sand. Certain of these crystals of carborundum, if mounted between metal clips or supports, are found to offer less resistance in one direction than in the opposite to an electric current. Hence such a crystal, when inserted in a circuit in which electric oscillations are produced, rectifies them or converts them into a direct current just as does the two-electrode or Fleming thermionic valve. Groups of electric oscillations can thus be rectified into intermittent gushes of electricity in one direction and thus affect a telephone receiver.

We are not able to say exactly at the present time what is the reason for this curious lopsided electric conductivity in certain crystals, but it must depend upon an asymmetry of structure. The same property is possessed by a native sulphide of molyb-

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denum called molybdenite, as found by Professor G. W. Pierce.

Also the contact point of many pairs of crystals or minerals has the same property.

If we place in contact a piece of zincite which is a natural oxide of zinc, and a piece of chalcopyrite, otherwise called copper pyrites, which is a sulphide of copper and iron, it is found that certain contact places have a rectifying power upon electric oscillations.

Again, the contact point of a bit of plumbago (black lead pencil) or the tip of a copper wire and a crystal of galena or sulphide of lead has a similar rectifying power. These crystals or contacts can therefore be used in series with a telephone receiver to rectify or convert into direct currents groups of electric oscillations. These then become audible as sounds in a telephone receiver, which are either continuous sounds cut up into Morse code signals in wireless telegraphy, or speech sounds as explained further on in wireless telephony.

In the common crystal receiving sets now being sold for broadcasting wireless telegraphy, the crystal is a specially treated piece of galena, and against it is pressed a flexible copper wire called a " cat whisker."

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CHAPTER VI

TELEPHONY AND SPEECH TRANSMISSION

33. Nature of Articulate Sounds.

BEFORE we can discuss the application of the scientific facts and principles previously described in the development of practical wireless telephony it will be desirable to preface it by a little further consideration of the physical nature of articulate sounds and some description of the instruments employed in the transformation of the energy of aerial vibrations involved into or from correspondingly varying electric current energy.

It has been explained that aerial waves consist in a state of compression at some point in the air, associated with an accompanying state of rarefaction, which states are not stationary at one place, but are propagated through the air with a velocity of about 1,100 ft. per second at ordinary temperatures. The production of these compressional and rarefactional regions is the result of oscillatory movements of the air particles moving to and fro along the line of propagation of the wave. If the motion of the air molecule resembles that of the bob of a long pendulum it is called a simple harmonic or simple periodic motion. The corre-

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sponding aerial waves are called simple harmonic waves, and the sensation they produce when acting on the human ear is that of a pure or simple tone such as that given out by a tuning fork or open organ pipe gently blown.

We have also explained that the oscillatory motion of the air particle may be of a more complicated nature, such that the displacement of the particle or the air pressure at any point and at various times can only be represented by the ordinates or heights of a complex curve called the wave-form curve, the horizontal distances representing the flow of *time*. The wave form of a pure musical tone, or simple harmonic wave, is a curve called a *sine curve* (see Fig. 74).

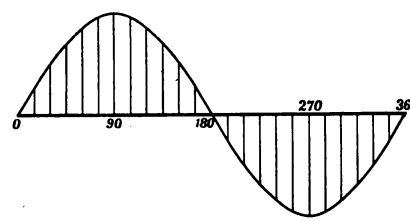


FIG. 74.—A simple sine curve, or simple harmonic curve, being the wave form of a pure musical tone.

It has been mentioned that, however complicated or irregular a wave form curve may be, it can always be imitated by adding together the ordinates of suitably placed simple harmonic curves of various amplitudes and of wavelength in the ratio of 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, etc., or some selection of such waves.

These last are called the harmonic constituents of the complex curve.

The equivalent statement in terms of sensations

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of sound is that any continuous sound having any *quality* corresponding to a certain wave form can be reproduced by simultaneous pure sounds or tones of suitable amplitude and phase difference. If, then, we consider the nature of the sounds made in articulate speech we find that very broadly they may be divided into two classes, viz., (i.) Continuous sounds, which are uttered by placing the mouth cavity, lips and tongue, in certain positions, and then forcing air out from the lungs. These sounds can be emitted as long as the breath lasts.

If we except certain sibilant hissing or rolling sounds, such as those indicated by the letters *s*, *sh*, *th* and *r*, we may call the remaining continuous sounds *vowel sounds*. In every language there are a large number of such sounds of different *quality*, and therefore, physically speaking, different wave forms. In English there are about 19 or 20 sounds which are expressed by different modes of sounding the so-called vowel letters *a*, *e*, *i*, *o*, *u*, or combinations of them, such as *au*, *ou*, *ei*, *æ*, *œ*, etc.

Then we have also (ii.) discontinuous or consonantal sounds, which for the most part are various irregular modes of beginning or ending the utterance of a vowel sound. All spoken languages are made up of certain vocal elements called *syllables*, which, combined together or alone, make *words*. A syllable comprises generally a vowel sound, which may be begun or ended with a consonantal sound or some other continuous sound of short duration.

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Physically speaking, and outside of ourselves, such syllabic sounds consist in short trains of damped aerial waves of complex wave form, and of a certain amplitude and wavelength, determining the loudness and pitch of the sound, the said trains being begun or ended, perhaps, in an abrupt or irregular manner corresponding to the consonant. The acquirement of a language consists in learning to associate particular vocal sounds, or groups of them, with certain objects, actions, or ideas.

The art of speech consists in being able to so control the vocal organs, larynx, lips, tongue, mouth cavity, breath, as to create the types of air wave trains which are by custom associated with certain ideas, things, actions, or wants. The human ear, by education, acquires an extraordinary power of distinguishing between the wave forms of aerial waves which strike the tympanum, and noting the manner in which this wave train begins and ends. If, for instance, we pronounce the monosyllabic words *day*, *die*, *do*, *dough*, or *tea*, *tie*, *too*, *toe*, we are, in fact, creating short rapidly damped wave trains of aerial waves differing somewhat in wave form and in the manner in which the wave train begins. Each of these sounds is associated in our minds with a thing or idea, and a *word* is therefore a more or less complicated sound of a certain finite duration and wave form which, when made, raises in the mind of a hearer an idea or conception similar to that in the mind of the speaker.

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In order that the word shall be correctly interpreted by the hearer, it is necessary that it shall be uttered with sufficient *loudness* and sufficient *clearness*. This implies that the sound waves must have adequate *amplitude* and sufficiently well defined *wave form* both in the terminal and medial portions of the wave train. The proper pronunciation of the terminal consonants in each syllable is important. Far too many people mumble or clip their words or run them together in speaking.

It is astonishing how few of those whose trade it is to speak in public, such as clergymen, barristers and politicians, are properly trained in the art of elocution.

34. Telephone Transmitters and Receivers.

The problem of transmitting speech to a distance, that is, the art of telephony, consists in arranging means by which the aerial vibrations constituting speech sounds which are uttered at one place can be reproduced at a distant place with sufficient amplitude and correctness of wave form to be heard and understood.

Although various attempts and suggestions for the solution of this problem had been made, no one had completely solved it until Alexander Graham Bell invented, in 1875, the speaking telephone, and this, coupled with the inventions of Edison, Hughes and others, as regards the carbon microphone transmitter, gave us practical telephony capable of

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operation in everyday life. Except in matters of detail, it is remarkable that the fundamental principles of the apparatus remain to-day what they were forty-six years ago.

Bell realised at a very early stage in his experiments that to achieve telephony by the aid of an electric current, the current in the wire must vary in strength with time exactly in accordance with the variations in air pressure made by the voice of the speaker at a point near his mouth. This means that the current must be an undulatory current.

Bell's solution of the problem of telephony was a remarkable stroke of genius, involving as it did the production of a novel yet most simple appliance which could act both as transmitter and receiver. He placed on the pole of a bar, or poles of a horse-shoe-shaped permanent magnet, soft iron pole pieces wound over with insulated wire. Very near to these pole pieces was fixed a circular flexible disc of thin iron about $2\frac{1}{4}$ ins. in diameter (see Fig. 76). When the coils of wire are traversed by a fluctuating electric current the magnetic poles are either weakened or strengthened a little. The disc, or diaphragm, as it is called, is therefore cupped, or bent in a little more, or else springs back suddenly. The amplitude of motion of the centre of the diaphragm is in any case extremely small, hardly ever exceeding 1/100th of a millimetre, yet the blow it inflicts on the air is sufficient to create an air wave, and therefore an audible sound, and the move-

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ments of the disc respond so quickly to changes in the current that the receiver can impress upon the

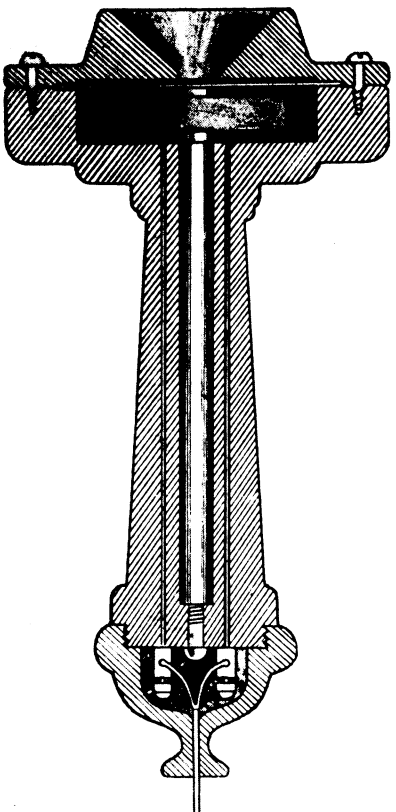


FIG. 75.—Section of a Bell magneto telephone.

air waves of a complex wave form which yield intelligible speech sounds.

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On the other hand, if we speak to the diaphragm the changes of air pressure made by the speech waves against the disc press it in or out. When the iron disc is moved nearer to the magnet poles it increases the pole strength slightly, and this creates an induced electric current in the surrounding coils of insulated wire, the variation in which copies to a certain extent the motion of the disc.

Hence, if two similar telephones have their coils joined by a pair of transmitting wires, speech made against the diaphragm of one telephone is faintly repeated by the diaphragm of the other, and the arrangement conveys audible speech to a distance.

It was, however, soon found that although the above-described Bell telephone is a remarkably good speech reproducer, it is not very effective as a transmitter, and it was soon replaced in this respect by the carbon microphone resulting from the discoveries and inventions of Edison and of Hughes.

In this transmitter the movements of the disc or diaphragm created by the speech sounds is made to compress more or less some granules of graphite, or hard conductive carbon, and this pressure varies the electric conductivity of the mass of granules. Hence, if this carbon forms part of the electric circuit of a voltaic battery, changes of current will take place in that circuit corresponding to the movements of the diaphragm.

Without entering into details of development we may describe one or two modern microphone trans-

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mitters as used in telephony, both with wire circuits and in wireless telephony as well.

In its usual form one of them is termed a "solid back" transmitter. It was invented by Mr. A. C. White, in America. It comprises an ebonite or glass trumpet-shaped mouthpiece, which may be replaced by a large metal cone, the function of which is to collect the sound waves and converge them on to a thin circular diaphragm or disc of aluminium, about $2\frac{1}{2}$ ins. in diameter, and about 1/50 in. in thickness. This diaphragm is clamped at the edges between rubber rings, and the speech waves collected by the mouthpiece or trumpet set the disc in vibration, pressing it inwards in concave form to an extent which depends on the amplitude of the sound wave and on the wave form of the latter, or else causing it to bulge out again. Behind this diaphragm is a small flat circular metal box carried on a rigid cross arm. The bottom of this box is covered with a thin disc of hard carbon like a wafer. The lid or top of the box is a thin mica disc, to the inside of which is clamped a similar hard carbon disc. There is a very shallow space between the two carbon discs, which is partly filled with small granules of graphitic carbon or coke (see Fig. 76). Wires are connected to the two carbon discs, and the centre of the mica diaphragm is connected by a metal screw with the centre of the aluminium diaphragm. Hence, when the latter is set in vibration by the speaking voice it causes a

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similar movement of the top carbon disc, and the carbon granules are more or less squeezed together, and their electrical resistance varied in the same manner as the movements of the outer diaphragm.

The electrical resistance of the carbon granules may be about 30 ohms in their normal condition, and it falls in resistance under the influence of the

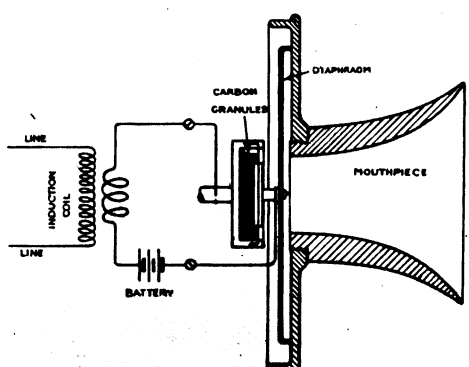


FIG. 76.—A solid back granular carbon microphone transmitter.

compression due to speech waves, but the actual variation of resistance in telephonic work is not more than about 5 or 10 ohms above or below the normal.

Another successful form of carbon transmitter is the Ericsson (see Fig. 77). In this case the diaphragm, which is acted upon by the speech sounds is a thin carbon disc 2·5 ins. in diameter and 0·04 in. in thickness. Behind this diaphragm is a carbon

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block, and a small interspace between the two is filled with small carbon granules. These are prevented from falling out by means of a ring of felt which encloses the circular carbon block. The normal resistance of this transmitter is 100 ohms, and it varies in operation between 50 and 170 ohms.

A trumpet-shaped mouthpiece is used to collect the sound waves and converge them on the diaphragm, and between the inner end of this trumpet

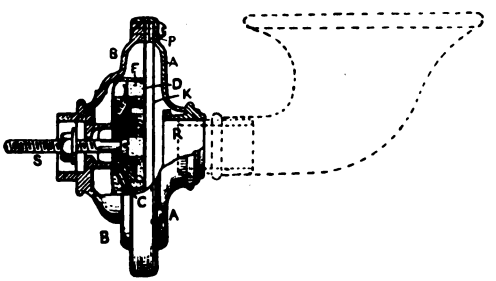


FIG. 77.—An Ericsson carbon microphone transmitter.

and the carbon diaphragm is a disc of oiled silk to keep the moisture of the breath from entering the microphone chamber. In most carbon granule microphones trouble sometimes arises from the "packing" of the granules, and from the sticking together of these granules, either due to moisture from the breath entering the granule chamber or from heat produced by the current.

The slight compressions due to speech movements of the diaphragm then fail to make the necessary variations in resistance.

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Another defect of the ordinary carbon granule transmitter is that it will not operate unless held with the plane of the diaphragm in a vertical position.

This difficulty has been overcome in the microphone, invented by Mr. J. Skinderviken, a Norwegian electrician, who constructs his transmitter box in the shape of a double cone. The diaphragm

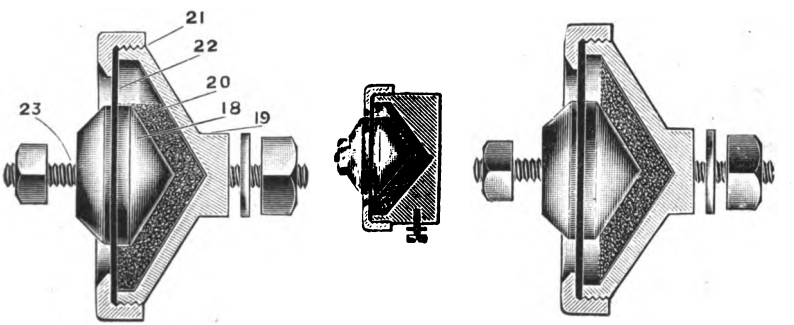


FIG. 77A.—Skinderviken transmitter.

has attached to it a convex cone of metal, and the carbon granules are contained between it and a concave metal cone, as shown in Fig. 77A. This arrangement permits the microphone to act in any position, as the carbon granules always must fill in part of the space between the two cones.

This form of carbon transmitter is known as the Skinderviken button transmitter. It has a higher resistance, and takes, therefore, less current than the usual type of carbon microphone; but, on the other hand, has a larger current-carrying capacity.

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The diaphragm, to which the conical metal button is attached, is made of aluminium, and no conical mouthpiece is required.

The carbon granule telephone transmitters in ordinary use, such as those above described, will not operate satisfactorily with more than about half an ampere of current passing through them. Hence, many arrangements were suggested for using a number of transmitters in parallel or together, but it is extremely difficult to secure an equal division of current between the instruments so that all the microphones shall take an equal share of the duty of modulating it. These arrangements need not be described, as they are now rendered unnecessary by the powers and remarkable properties of the thermionic valve as described later on. It is, however, necessary in nearly all cases to associate with the microphone an induction coil for the following reasons.

The variation in resistance of the carbon granule microphone is, in general, only a fraction of its normal resistance, which may be from 30 to 100 ohms. Suppose, then, that such a microphone, in series with a few cells of a battery, is placed in a circuit which has a much higher electrical resistance than the microphone itself. It will be evident that any variation in resistance of the microphone produced by speech made against the diaphragm will only vary the total resistance of the circuit by a much smaller percentage than that by which the

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resistance of the carbon microphone itself is varied (see Fig. 78).

This difficulty is overcome by the use of an induction coil as first suggested by Edison. We provide a small induction coil *T*, consisting of two insulated wires wound over a small bundle of iron wires (see Fig. 78). The resistance of one primary wire may be about 1 ohm, and the resistance of the other, or secondary wire, may be about 25 ohms. If, then, we join in series the primary wire and the carbon microphone *M* and a battery *B* of a few low-resistance cells, it will be evident that any variation in the resistance of the carbon microphone due to vibrations of its diaphragm will create variations in the current flowing through the circuit of nearly equal percentage to the variations in microphone resistance. Then any changes in the current flowing through the primary wire of the induction coil will create corresponding variations in the electromotive force induced in the secondary wire.

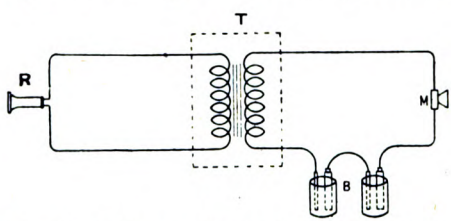


FIG. 78.—A diagram illustrating a simple telephone circuit. *M* is the carbon microphone transmitter, *B* is the battery, *T* the telephone induction coil, and *R* is the receiving telephone.

The line wires are attached in ordinary wire telephony to the terminals of this secondary circuit, so that the current transmitted is an

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induced current, and this passes through the receiver telephone *R* at the listening end.

In the case of wireless telephony, as will be explained later on, the secondary electromotive force is used to vary the potential of the grid of a thermionic valve called a control valve.

A method which avoids the use of an induction coil is to join a number of microphone transmitters in series, so that they are all equally affected by the voice, but the total resistance variation is then the sum of the variations of each microphone separately.

Great ingenuity has also been expended in the invention of liquid microphones, such as those of Q. Majorana and J. Vanni, or by using continually renewed supplies of carbon granules as in the falling carbon powder microphone of Marzi. Nevertheless, the only type of telephone transmitter which has obtained extensive use in practical telephony is the carbon granule microphone.

In arrangements for wireless telephony employed before the application of the thermionic valve as a generator of continuous waves, it was necessary to modulate rather large currents of 5 or 10 amperes by a microphone transmitter.

The construction of the Bell magneto-receiving telephone has been the subject of numerous improvements in details of construction. In place of a single steel bar magnet as originally used, two bar magnets made of tungsten steel are used, which are fixed parallel to each other at a little distance

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apart, and connected at one end by an iron distance piece, or else an elongated horseshoe magnet is employed (see Fig. 79). On the free outer poles are fixed L-shaped soft iron pole pieces, on which coils of insulated wire are wound. The magnets are contained in a non-magnetic metal tube, which is wider at the outer end. On this outer end is fixed a thin disc made of a steel called "Stalloy," which contains about 2·75 per cent. of silicon. This steel disc is about $2\frac{1}{4}$ ins. in diameter, and 1/100th in. in thickness. This diaphragm is so fixed that there is an interspace of about 0·016 in., or about 1/60th of an inch between the flat ends of the pole pieces and the inner surface of the metal disc. The lines of magnetic force which spring from one pole of the magnet pass across this air gap through the iron diaphragm, and back across the air gap to the other magnet pole. The circular diaphragm is therefore sucked or cupped in at the centre, due to the magnetic pull of these poles. If, then, an electric current is sent through the coils of wire wound on the pole pieces it will either increase or else weaken this attraction. If we call *H* the magnetic force due to the magnet alone, and

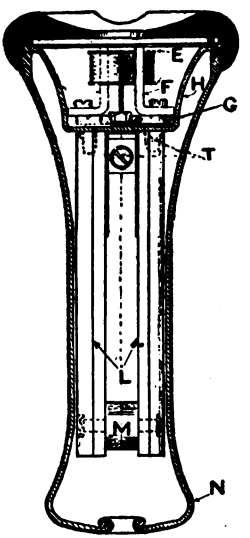


FIG. 79.—British Post Office type of magneto telephone receiver.

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h the magnetic force due to the current in the coils, then the force can vary from $H + h$ to $H - h$, according to the direction of the current. The attraction or pull on the diaphragm varies as the square of the magnetic force or flux, as it should be called, and hence the attractive force varies between $(H + h^2)$ and $(H - h^2)$. The difference is $4Hh$, and hence depends on H as well as h. It is therefore important to have magnets in the receiver as strong as possible. The material generally used for them is steel containing 5 or 6 per cent. of tungsten, and 1 or 2 per cent. of chromium. The finished magnets are made very hard by quenching from a red heat in ice-cooled water to give them the power of retaining magnetism. Recently a type of steel has been invented at Sheffield called *cobaltcrom*, containing about 15 per cent. of cobalt and 15 per cent. of chromium. It has a much higher magnetic coercive force than tungsten steel. Moreover, it stores up about double the magnetic energy for the same volume of metal. It has the great advantage that it does not require hardening from a red heat in a liquid, and hence the finished magnets are not so liable to be warped out of shape in quenching.

It is important that the small air gap between the magnet poles and the diaphragm should remain of perfectly constant width. The coils of wire wound on the soft iron pole pieces are made of fine silk-covered copper wire, and may be of resistance

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between 60 ohms and 4,000, according to the purposes for which the receiver is used.

In wireless telephony the type of receiver generally employed is called a double head telephone. It has two receivers of watch shape, attached by flexible joints to a steel or aluminium head-band, which passes over the top of the operator's head and holds the two receivers against the ears.

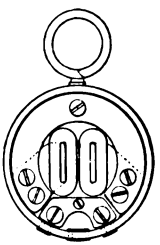


FIG. 80.—Watch form of magneto-telephone receiver with the diaphragm removed to show the magnet and the coils.

The receivers are in circular watch-shaped cases, made of ebonite or aluminium (see Fig. 80). The magnets are flat rings of steel, with L-shaped soft iron pole pieces screwed into them, on which are wound rectangular shaped coils of extremely fine silk-covered copper wire

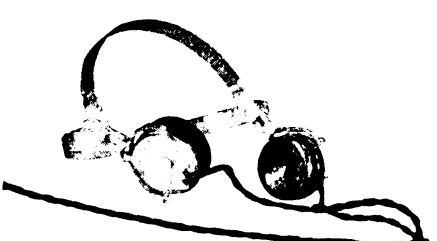


FIG. 81.—Double head telephone receiver with spring head band (S. G. Brown).

(No. 40, or even No. 60, standard wire gauge), so as to obtain a very high resistance of 2,000 to

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4,000 ohms. The two receivers on the headband have their coil circuits in parallel (see Fig. 81).

In the case of loud-speaking receivers the construction is the same as in the portable receivers, but the magnets and diaphragms are larger, and a trumpet-shaped sound projector, like the horn of a gramophone, is attached. A very good example of this type of instrument is the loud speaker of Mr. S. G. Brown, by which telephonic speech can be heard by several hundred persons at once in a large theatre (see Fig. 82).



FIG. 82.—Loud speaking telephone of S. G. Brown.

Mr. Brown has also invented very excellent forms of double head telephones, which are in extensive use for wireless telegraphy and telephony. He has devised a form of aluminium headband and self-adjusting swivel receiver holders which are comfortable to wear on the head, and by which the receivers are kept gently pressed against the ears (see Fig. 81). The electrical construction of the receivers, as used for wireless telegraphy, is some-

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what different to the standard magneto pattern. In place of an iron diaphragm there is an iron reed, or strip of iron, the natural vibration frequency of which can be adjusted by a screw within limits. To this is screwed an aluminium diaphragm, which is coned and spun into a special fitment, which is covered by an ebonite cap with holes in the centre (see Fig. 83). The resonance frequency of this receiver can therefore be adjusted to suit the musical note of the wireless signals in telegraphy.

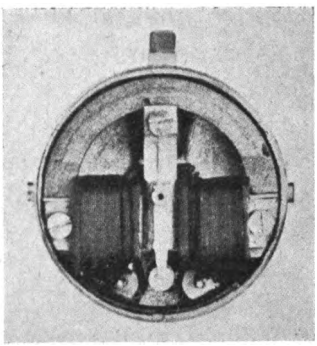


FIG. 83.—Interior construction of the resonance telephone receiver of S. G. Brown, showing the vibrating steel reed.

In the case of receivers for wireless telephony this adjustment is not required, but the resonance frequency is adjusted to agree with the mean or standard telephone frequency, generally about 800 or 900 cycles per second. The coils of receivers for wireless telephony in use with valve or crystal receiving sets are now always wound with a direct current resistance of about 4,000 ohms.

35. EFFICIENCY AND PROPERTIES OF THE TELEPHONE RECEIVER.

The remarkable fact about a Bell magneto telephone is that the mere vibrations of a small flexible

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circular iron disc should be capable of impressing on the air waves having the very irregular wave form necessary to create speech sounds. When we consider the complicated nature of our own human organs of speech and the manner in which the larynx, throat muscles, variable mouth cavity, lips, tongue and teeth, are all brought into operation to create articulate sounds, it is wonderful that the mere to and fro motion of a small thin iron disc can do nearly the same thing in creating speech. Another striking thing is the very small electric currents which are capable of creating audible sounds in a telephone receiver, and the extremely small amplitude or extent of motion of the telephone diaphragm in creating such sounds. P. E. Shaw measured, in 1905, the amplitude of diaphragm motion for a just audible sound in a magneto receiver, and found it to be about one-fourteenth part of a millionth of a centimetre, or about one-thirty-fifth part of a millionth of an inch.

The diaphragm of a telephone has, however, a certain natural frequency to which it best responds. It resembles a violin string or harmonium reed in that there is no particular natural frequency at which it will vibrate and yield its fundamental note if it is struck and left to itself. This frequency is called its *resonance frequency*, and in telephones with iron diaphragms about 2 ins. in diameter and 1/50th in. thick. the resonance frequency is about 800 or 900. Hence, if we pass through the telephone coils

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an alternating electric current having this resonance frequency, the amplitude of motion of the diaphragm will be increased from 10 to 30 times when compared with that which it would have for the same current at a different frequency.

In connection with telephone work we require to give numerical values to the loudness of various sounds heard in the telephone. This is stated in terms of their *audibility*. If we pass an alternating current through a telephone of any frequency between, say, 100 and 2,000, we hear, on listening to the receiver, a more or less musical sound. If we apply across the terminals of the telephone a resistance called a shunt, which has no inductance, and gradually decrease this resistance, we shall at last reach a point at which the telephone sound is only just audible, because part of the current is shunted away from its coils. If the resistance of the telephone coils is R ohms, and the resistance of the shunt is then S ohms, then the *audibility* of the sound when the shunt is removed is expressed by the number $(R + S)/S$. Strictly speaking, we should say impedances and not resistances. Thus, suppose the telephone had an impedance of 100 ohms, and that we had to shunt the telephone with 2 ohms to just make the sound heard in the telephone inaudible to a normal ear, then the so-called audibility of that sound when the shunt is removed would be $102 \div 2 = 51$.

Shaw found that if the audibility of a just percep-

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tible sound is taken as unity, then the audibility of a loud sound would be about 1,400, and that of an overpowering sound 7,000 or more. Broadly speaking, we may say that the intensity of the sounds emitted may vary from 1, which denotes a just audible sound, to 1,000, which denotes a fairly loud sound.

The displacement or amplitude of motion of the diaphragm may vary from about half a micron ($= 5 \times 10^{-5}$ cm.), which is about the wavelength of a ray of yellow light, to 8 or 10 microns, which is about 1/100th of a millimetre. Even in the case of loud telephonic sounds it is very small.

As regards the currents required to produce sounds of various audibilities, Werner Siemens long ago found that with a particular Bell telephone, the interruption of a current of 1/50,000th of a milliampere, when passed through the coils, caused the diaphragm to emit a just audible sound or tick. With more modern receivers the starting or stopping of a current of not more than 1/6th of the above could be detected. If, however, alternating currents are used, the current producing a just audible sound would depend upon whether the frequency of that current agreed with the telephone resonance frequency or not.

Another very remarkable quality of the magneto telephone is its astonishing inefficiency as an energy transforming device. We employ a magneto telephone to transform the energy of the varying electric

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currents sent through it into energy of aerial sound waves. But the fraction of the energy it so transforms is at most about 1/1,000th or 1/10th of 1 per cent., and, except at resonance frequency, may be only a few parts in 100,000.

The greater part of the electric power given to the coils of a telephone receiver is expended in producing heat in the wire coils and in the diaphragm, in mechanical work in bending the diaphragm and moving it to and fro, and in magnetic energy losses in it, and at most one or two parts in 1,000 of all the power applied is utilised in the production of the speech sound waves.

There is, therefore, a vast field for possible improvements, and it is curious that, with the exception of the hot wire telephone or thermophone receiver of De Lange and O. Fischer, invented in Holland, there has been no great departure from the principles of Bell's invention made 47 years ago, although very considerable improvement has taken place in details and in manufacture.

The thermophone consists of a little loop of very fine platinum wire, which is contained in a little ebonite tube. This tube is inserted in the orifice of the ear. When the telephonic speech electric currents pass through this wire they heat it and cause a sudden expansion of the air in the tube. This action creates aerial waves which are heard as speech by the ear.

Another type of thermal receiver is that invented

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by Mr. Leslie Miller, which he calls a loose contact receiver.

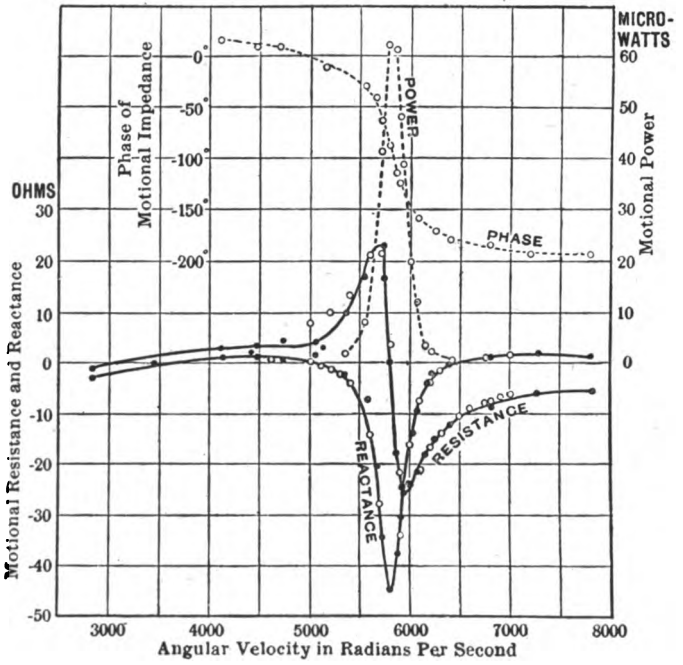
To the back of a mica diaphragm is attached a small disc of carbon, and a metal or carbon point just touches this disc. A continuous electric current is passed through this loose contact. When the telephonic currents are also sent across this contact they cause the loose contact to widen out or contract, and thus set the diaphragm in vibration. This in turn creates aerial waves and so reproduces speech sounds. These various types of thermal receiver are interesting and of possible value, but have not yet displaced in practice the Bell magneto telephone.

Much research has lately been conducted on the properties of the magneto telephone receiver. Many interesting monographs have been published by Prof. A. E. Kennelly and his associates in the Massachusetts Institute of Technology, U.S.A. Kennelly has made measurements, at various frequencies and with different receivers of standard types, of the true resistance, the reactance, and the impedance of the telephone coils.

In general, the resistance of a telephone is reckoned as the resistance to direct currents. Thus, we speak of a 60-ohm telephone, meaning one of which the coils measure 60 ohms with direct current. The speech currents are, however, alternating currents with a frequency varying from 100 to 2,000, and a mean value of about 800 or 900,

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corresponding to the resonance frequency of the telephone. The resistance R with high-frequency



(a)

FIG. 84.—Curves obtained by Dr. A. E. Kennelly for the motional resistance, reactance and power absorption of a magneto-telephone receiver. Note—The angular velocity signifies 6·28 times the frequency of the alternating current.

currents is much greater, perhaps double or more, compared with the direct current resistance. Again, if we measure the inductance L of the coils at any frequency n, then the product $2\pi nL = wL$ is called

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the *reactance* of the coils, and the quantity $\sqrt{R^2 + w^2L_2}$ is called the *impedance*.

If the resistance, reactance, and impedance of a telephone receiver are measured at the same frequency—first when the telephone is emitting sound, and secondly with the diaphragm clamped, so that no sound is emitted—and if we subtract the second measurements from the first, the difference gives us the so-called *motional* resistance, reactance, and impedance of the telephone. If these are measured at different frequencies, and the values plotted as the ordinates of a curve corresponding to the various frequencies as abscissæ, we obtain a set of interesting curves (see Fig. 84). The motional resistance at frequencies far from the resonance frequency is small, then it rises to a maximum, and then suddenly falls to zero at resonance, and passes to a negative maximum. The motional reactance is always negative and a maximum at resonance. The motional power is a maximum at resonance; that means when the frequency of the alternating current used in the measurement agrees with the natural frequency of the telephone diaphragm.

On the other hand, if we plot the motional resistance horizontally and the motional resistance downwards vertically (see Fig. 85), we obtain a circle called the *motional impedance circle*, the diameter of which measures the impedance of the telephone at resonance frequency. The angle

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which any chord of this circle makes with the horizontal line is called the *depression angle*, and

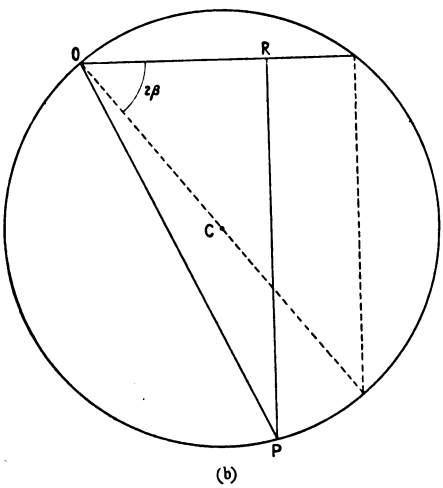


FIG. 85.—Circle of motional impedance constructed by plotting the motional resistance horizontally *OR* and the motional resistance downwards vertically *RP*, the diameter of the circle measuring the impedance of the telephone.

this angle is double of the angle by which the magnetic flux in the telephone magnet lags behind the magnetising force.

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CHAPTER VII

THE PRINCIPLES OF WIRELESS TELEPHONY

36. Production of Continuous Electric Waves.

IT is now possible to gather up the threads of all previous explanations and utilise them in making an exposition of the principles and mode of operation of the wireless telephone, which is certainly one of the most wonderful of all the achievements of technical science.

To conduct wireless telephony as contrasted with telephony with line wires, we have to replace the line wire by some agency which will enable us to transmit energy and yet permit us to employ the usual type of microphone transmitter and magneto-receiver used in ordinary telephony with wires at the sending and receiving stations. It has been found that we can do this by substituting for the connecting wire a stream of undamped or continuous high frequency electromagnetic waves. We must, then, first explain how these waves are created.

There is only one method practically employed at present in small plants, or those of moderate

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size, and that is by means of the thermionic valve. We have already explained that an incandescent tungsten filament in vacuo emits a torrent of electrons, and that these in the three-electrode valve make their way through the apertures of the surrounding grid and fall upon an anode or collecting plate. To make them do this the anode must be kept at a high positive potential so as to attract to it the negative electrons. This is done by means of a battery, dynamo, or other source of direct electromotive force. The anode must be connected to the filament by an external circuit which includes the above-mentioned source of electromotive force, but also a coil of wire called the plate circuit coil. This plate circuit coil has also its terminals connected to a condenser of a certain capacity, so that the coil and condenser, taken together, provide a circuit in which electric oscillations can take place with a certain natural frequency determined by the capacity of the condenser and the inductance of the coil in accordance with rules already given.

If, then, the grid is connected to the filament through another circuit which also includes a coil of wire, and if this last coil, called the grid circuit coil, is placed near to the plate circuit coil and in a certain position, any change in the current in the plate circuit coil will create an induced electromotive force in the grid circuit coil, and this in turn will alter the grid potential and charge the grid

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either negatively, that is put more electrons into it, or positively, that is take free electrons from it. When the grid is made negative it will reduce the electron stream flowing from the filament to the plate, and reduce the current in the external plate circuit or coil. By a proper mode of connection it is possible to make the changes of grid electrification of such sign and nature as to sustain the fluctuations of the plate current, which, in turn, by the mutual inductive action of the plate and grid coils, create the appropriate variations of grid potential.

The grid and plate coils are then said to be coupled for production of oscillations. The plate current then consists of a steady direct current, on which is superimposed an alternating current, or the plate current fluctuates in strength. The power required to produce these oscillations comes from the battery in the plate circuit, but the power is transformed from direct current (D.C.) power to alternating current (A.C.) power.

The action of the thermionic valve in this respect has been compared with a steam engine. The steady pressure of the steam is applied to push forward the piston, but to make the piston oscillate, or move backwards and forwards alternately, the steam must be admitted to the cylinder by means of the slide valve, first on one side of the piston and then on the other. To make the engine self-acting we have to connect the slide valve by some

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mechanism with the piston so that motions of the piston move the slide valve in the proper manner to maintain the oscillations of the piston. The steam may be compared with the electrons emitted by the filament; the grid is analogous to the slide valve, and the external plate current to the motions of the piston.

The above analogy is, however, very imperfect, and a much better one is as follows: If we connect together in series a Bell magneto telephone, a carbon granule microphone transmitter, and a couple of cells of a battery, a current will flow through the carbon and through the coils of the telephone. If we hold the diaphragms of the transmitter and receiver near together the receiver will emit a shrill musical note, and continue to emit it as long as the two instruments are close together.

The reason is as follows. Small noises in the room set the diaphragm of the transmitter in vibration. This causes compression of the carbon granules, and in turn varies the current, and this makes the receiver emit a sound. This sound actuates the transmitter, and this again reacts on the receiver. Hence continuous sound waves are emitted by the system, and the power to produce them is drawn from the battery.

Just as this coupled receiver and transmitter generate low frequency oscillations of electric current in their circuit, so the coupled thermionic

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valve circuits react on each other and create high or low frequency electric oscillations in the plate circuit according to the capacity and inductance in the circuit. To radiate electromagnetic waves we have to utilise these oscillations to produce similar oscillations in an *aerial wire*, or radiative circuit. The simplest method, then, of producing undamped or continuous waves (C.W.) by a

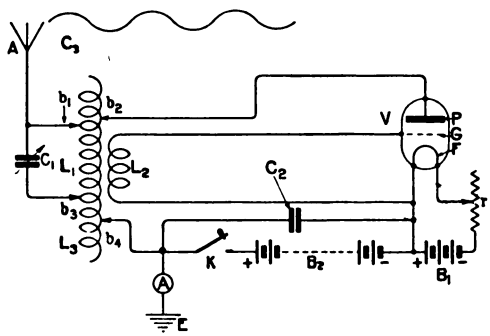


FIG. 86.—Arrangement of circuits for producing continuous electric waves (C.W.) by a thermionic valve.

thermionic valve is by an arrangement as follows :—

Let V (see Fig. 86) be the valve of which P is the plate or anode cylinder, G the grid, and F the filament. Let B_1 be the battery which provides current for incandescing the filament, and r the regulating resistance. Let the grid be connected with the filament through a coil of wire L_2, called the grid coil, and let the plate P be connected with

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the filament through another coil L_1 and a key K, and high voltage battery B_2 giving a voltage of 200 to 400 volts or more. The negative terminal of B_2 must be in connection with the filament. This battery B_2 must be shunted by a condenser C_2. The coil L_1 is also shunted by a condenser C_1. If the degree of coupling or closeness of the coils L_1, L_2 is adjusted, and the direction of their mutual inductance correct, then, as already explained, continuous oscillations will be set up in the circuit of L_1 which are superimposed upon the steady or direct current produced by the battery B_2. The frequency (n) of these oscillations will be determined by the capacity of the condenser C_1 and the inductance of the coil L_1 in such fashion that—

$$n = \frac{5033}{\sqrt{C_1 L_1}}$$

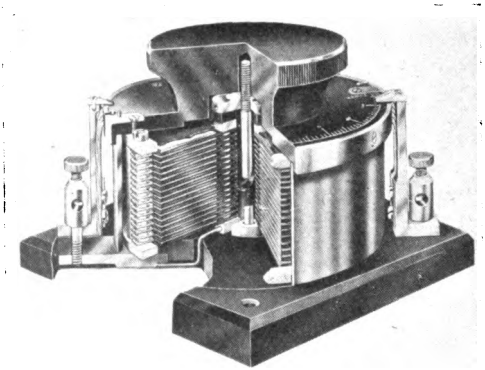
The capacity C_1 must be measured in microfarads or fractions of a microfarad, and L_1 must be measured in millihenrys, or fractions of a millihenry, and the square root of the numerical product of C_1 and L_1 divided into the number 5033.

The condenser C_1 is connected to the coil L_1 by sliding contacts b_1, b_3 so that the inductance L_1 can be varied. Also the condenser C_1 is an adjustable capacity indicated symbolically by the arrow crossing two parallel black lines.

In actual practice the coil L_1 is made by winding

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enamelled copper wire in close turns on an ebonite or fibre tube about 4 or 6 ins. in diameter. The enamel is then scraped or rubbed off a narrow strip parallel to the length of the cylinder, and enables rubbing contacts of brass to be slid along a bar and



By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 87.—An air condenser of variable capacity formed with a set of fixed semi-circular metal plates and similar movable plates, which latter can be brought more or less into proximity to the former by rotating the ebonite head of the axis carrying the movable plates. N.B.—Part of the condenser in this illustration is shown cut away so as to enable the structure to be seen and understood.

so make contacts at places b_1, b_2, b_3, b_4, as desired with the copper wire. The condenser C_1 is made of a number of semi-circular plates of aluminium, spaced a little way apart, which are attached to an axis. These plates are so fixed that they can be turned to sandwich in, more or less, between a number of fixed semi-circular plates. The fixed and movable plates

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are the two plates of the condenser, and by rotating the movable plates so as to bring them more or less in between the fixed plates, the capacity of the condenser is varied (see Fig. 87).

37. Radiation of Continuous Waves.

We have next to make provision for using these oscillations to create continuous electric waves. We have seen that when high frequency oscillations are set up in a straight rod or wire with metal plates at the end, called a Hertzian oscillator, the result is to radiate electromagnetic waves which we have explained to be vibrations propagated along the electro-lines proceeding from the free electrons in the wire, the rapid to and fro movements of which are the electric oscillations in that wire.

This radiation is effected by connecting to the contact b_1 an aerial wire A, which consists of two or more copper wires which rise vertically into the air a certain height, and then run horizontally a certain distance, and are insulated at the far or free end (see Fig. 86). At the same time we connect another point b_4 on the inductance coil L_1 through a current-reading instrument A, called a hot wire ammeter, to a plate E sunk in the earth, or it may be the water-pipes of a building.

The aerial A has a certain electrical capacity with respect to the earth, and may be regarded, therefore, as another condenser joined across a section of the coil L_1 between the points b_1 and b_4. By suitably

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choosing the points of contact b_3 and b_4, we can tune together the oscillatory circuits composed respectively of the condenser of capacity C_1 and the section L_1 of the inductance coil, and also the capacity C_3 of the aerial and the section $L_1 + L_3$ of the inductance coil, by making the adjustments so that the product C_1L_1 is equal to the product $C_3 (L_1 + L_1)$.

If, then, we close the key K, the battery B_2 will send a stream of electrons from the filament of the valve to the plate, and they will find their way back through the coil L_1. If the grid then becomes slightly negative the electron stream from the battery will be reduced, and by the inductive action of the coils L_1 and L_2 this reduction of plate current can be made to give the grid a slight positive charge, and this then increases the electron stream. Accordingly fluctuations are set up in the plate current. The object of the condenser C_2 shunted across the high voltage battery is to provide a path for the high frequency oscillations thus created in the plate circuit. The varying potential of the terminals of the condenser C_1 then sets up sympathetic oscillations in the aerial wire, and this results in electromagnetic waves being radiated from it in an uninterrupted stream. The ammeter A placed just above the earth plate E then indicates a steady high frequency current, which is called the aerial current.

In the actual apparatus the two coils L_1 and L_2

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are wound on ebonite tubes or in flat spirals, and so arranged that they can be brought near to or separated from each other to vary the mutual inductance. This coupling must exceed a certain value if the oscillations are to be created by the thermionic valve and electric waves radiated from the aerial. We can determine the frequency of the oscillations when we know the wavelength required or used from the simple relation—

frequency × *wavelength* = *velocity of wave.*

The velocity of electromagnetic waves through air is nearly 300,000 kilometres per second. Hence, to produce a wave of 300 metres wavelength requires oscillations at the rate of one million per second in the aerial. The standard wavelengths for amateur wireless telephony and for "broadcasting" lie between 100 and 200 and 350 and 425 metres. Hence a 400 metres wave requires 750,000 oscillations per second in the aerial. Let us then suppose that we have set up at some place an aerial and continuous wave (C.W.) generating valve plant, as above described. We can suppose it set in operation and to radiate continuous waves, say, of 400 metres wavelength. These waves are called the *carrier waves.*

Next, suppose we have at some other place a receiving station at which there is an aerial properly tuned to the wavelength of the wave sent out by the generating station, and that this receiving aerial is

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coupled to another closed oscillatory circuit comprising an inductance coil and a condenser with the capacity adjusted to tune it to the aerial circuit (see Fig. 88).

The waves from the transmitting station would strike the aerial of the receiving station and would set up in it feeble electric oscillations of the same frequency. These would generate other similar

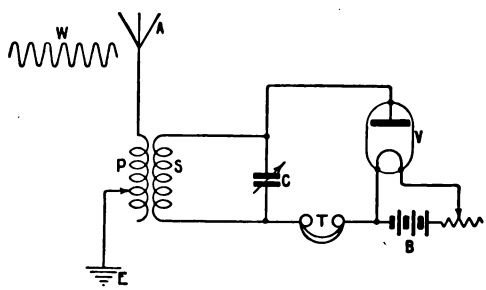


FIG. 88.—Simple form of receiving circuit for wireless telephony. *A* is the aerial, *P* the aerial tuning coil, *C* is the tuning condenser and *V* a Fleming rectifying valve, *T* is the telephone. *W* represents the arriving carrier waves.

oscillations in the associated closed condenser circuit. The terminals of this last condenser would then alternate in potential alternately being positive and negative.

Suppose, next, that we connect these condenser terminals to the plate and filament of a two-electrode rectifying valve in series with a telephone as in Fig. 88.

The valve, when its filament is incandescent, would permit negative electricity or electrons to

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pass from the filament to the plate inside the bulb, but not in the opposite direction. Hence, the telephone coils would be traversed by a steady unidirectional or direct current.

This kind of current produces no effect on the telephone except to create a slight "tick" or sound at the moment the steady current begins or

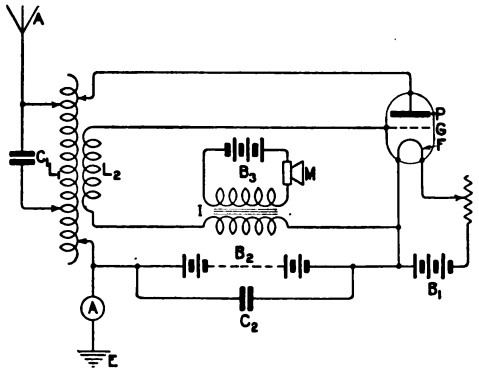


FIG. 89.—Circuits of a simple form of wireless telephone transmitter showing the speaking microphone M coupled inductively through an induction coil I to the grid circuit L_2 of the thermionic valve.

ends. Suppose then that we insert in the external grid circuit of the valve in the transmitting apparatus the secondary circuit of a small telephone induction coil I (see Fig. 89), and in the primary circuit of the coil a carbon microphone M and battery B_3. If we speak to this microphone mouthpiece the result will be to create in the grid circuit a fluctuating electromotive force, which will have

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the wave form of the speech sound, and will have a low frequency or *audio-frequency*, as it is called, because it falls within the limits of the frequencies used in audible speech.

The effect of this will be to increase or diminish the amplitude of the carrier waves radiated. In other words, the speech made to the carbon microphone *M* will modulate the amplitude or height of the carrier waves exactly in accordance with the frequency and wave form of the aerial vibrations made by the voice of the speaker.

Let us then consider what the effect of this will be on the receiving apparatus just described. Any increase or decrease in the amplitude of the carrier waves will increase or decrease in the same proportion the direct or rectified current which flows through the magneto telephone in series with the rectifying valve. Hence, if speech is made to the microphone transmitter inserted in the grid circuit of the transmitting valve, the current in the sending aerial, and the amplitude of the carrier waves and therefore the current through the Bell telephone in the receiving current, will vary or change in nearly the same manner as the changes of air pressure made by the voice of the speaker near the microphone.

38. Practical Forms of Wireless Telephone Apparatus.

In actual practice the apparatus is a little more complicated. The high voltage required for the

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plate of the transmitting valve is not always obtained from a battery, but from a direct current dynamo which gives a voltage of several hundred or even a couple of thousand volts.

Then the modulation of the plate current is not accomplished by placing the microphone-induction coil in the grid circuit of the oscillating valve, but in that of another valve called the control valve.

Lastly, the high voltage of the plate of the generating valve need not be obtained from a direct current dynamo, but by rectifying a low-frequency alternating current.

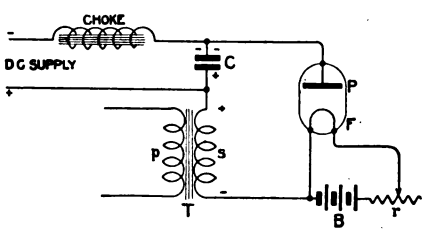


FIG. 90.—Arrangement of circuits for rectifying an alternating current supplied from a transformer *T* by means of a Fleming valve and condenser *C*.

These modifications will best be understood by the description of certain typical forms of wireless telephone transmitter in actual use.

It will perhaps be advisable first to explain the manner of using a two-electrode or Fleming valve to rectify high voltage alternating electromotive force, or change it to direct voltage.

If we connect to the plate *P* of a two-electrode valve one terminal of a condenser *C*, the other terminal of which is connected through the secondary coil *S* of an alternating current transformer *T* to the filament *F* of the valve (see Fig. 90), and if we

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supply the transformer with low-frequency alternating current, then the plate of the condenser, which is directly connected to the anode or metal cylinder of the valve, will become charged with negative electricity.

The reason is as follows: When the direction of the E.M.F. in the transformer circuit *s* is such as to make the plate *P* of the valve positively electrified, electrons are drawn out of the incandescent filament *F*, and neutralise this positive charge of the plate. The upper plate of the condenser *C* is then left negatively electrified. When the E.M.F. of the transformer reverses, and the plate *P* becomes negative, it repels the escaping electrons and stops the emission from the filament. Hence, if the condenser *C* has a large capacity it will become a reservoir of electricity, and we can continually draw off from it a supply of negative electrons from its upper plate. As these electrons are supplied in gushes by the transformer, it is found advantageous to insert a spiral of insulated wire wound on a bundle of iron wires, called a choking coil or choker, as shown in Fig. 90. This serves to convert the intermittent gushes of electrons into a steady stream, which can be drawn off the *d. c.* terminals marked + and —.

In the above-described arrangement we only utilise and rectify every alternate phase, or half of the alternating current energy. By the use of two rectifying valves and a transformer with a connection to the

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centre of its secondary circuit, as shown in Fig. 91, we can rectify both phases, and convert all the alternating power of a transformer into direct current power. The two valves can have their filaments rendered incandescent by the same filament heating battery *B*. The reservoir condenser *C* has choke coils inserted in its exit wires marked *d. c.* + and —, and from these we can draw off direct current with a steady E.M.F.

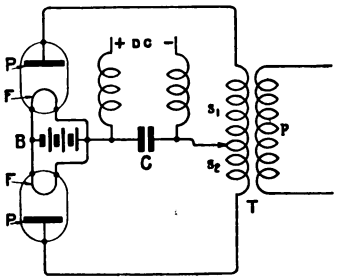


FIG. 91.—Arrangement of circuits for rectifying both components of an alternating current supplied by a transformer *T* by means of two Fleming valves. The condenser *C* then supplies a direct current.

The above appliances are all combined in the half-kilowatt wireless telephone cabinet designed by Marconi's Wireless Telegraph Company for radio-telephony. This consists of a cabinet, in shape like a harmonium case or small piano, about 4 ft. high and wide, and 2 ft. deep. It contains all the transmitting and receiving gear effective for wireless telephony over a range of about 100 miles by day, but greater by night. This range corresponds to use with aerial wires of twin T type, 220 ft. long, and 100 ft. high, with a natural wavelength of 360 metres. A view of the front of the cabinet is shown in Fig. 92.

The transmitting part comprises three thermionic

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valves, two of three electrodes and one two-electrode rectifying valve. A picture of one of these valves is shown in Fig. 93.

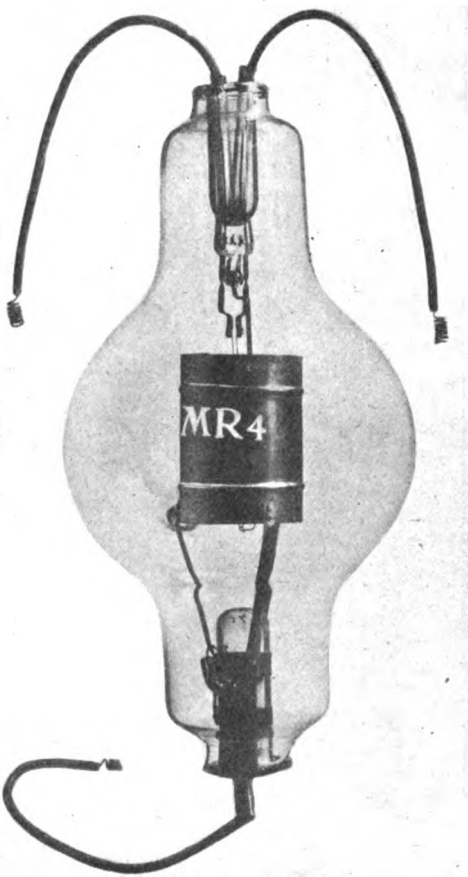


By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 92.—Half-kilowatt valve transmitting set for wireless telephone as arranged by Marconi's Wireless Telegraph Co., Ltd. The transmitting valves are shown in the centre panel and the receiving valves on the right-hand bottom panel.

In the actual transmitter, a view of which is shown in Fig. 92, one of the three-electrode valves in the centre panel is the power or generating

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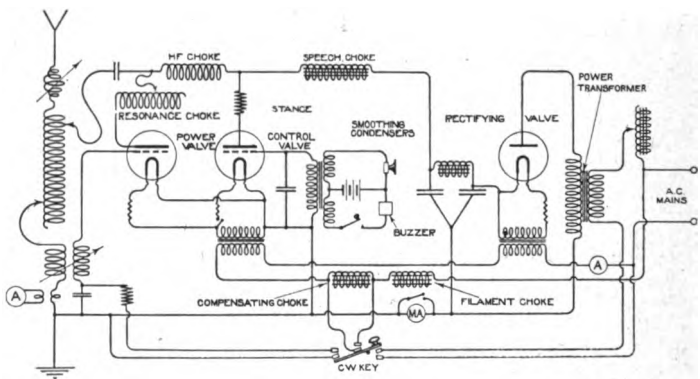
FIG. 93.—Large three-electrode transmitting thermionic valve for generating high frequency alternating currents.

valve; the other is the control valve; and the two-electrode valve is used for rectifying the

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alternate current supplied by a transformer in one of the lower cupboards, taking its primary current from a rotary converter, which transforms direct electric current into alternating current at a frequency of 150 cycles and 85 volts E.M.F.

The diagram of connections is shown in Fig. 94.



By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 94.—Diagram of connections in the transmitter part of the half-kilowatt wireless telephone apparatus shown in Fig. 92.

It will be seen that the alternating current supply (A.C.) is fed into an alternating current transformer called the power transformer, and also into two smaller transformers which step down the voltage, and supply current at 12 volts for heating the filaments of the three valves. The electromotive force of the power transformer is rectified by the two-electrode valve on the right hand side of the diagram, and used to charge two reservoir con-

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densers connected to a smoothing choking coil, and these condensers supply a steady or direct high voltage to the plates or anodes of the two three-electrode valves on the left of the diagram. The valve marked "power valve" has its plate and grid circuits coupled through a reaction coil, and high frequency oscillations are therefore created in the coil L_1, to the upper end of which is attached the aerial wave A, and its lower end to an earth plate. Continuous or undamped carrier waves are accordingly radiated from the aerial.

The amplitude of these waves is controlled by the microphone M in conjunction with the control valve (middle). It will be seen from the diagram that the grid of this control valve is connected to the secondary terminal of a transformer, in the primary circuit of which is a 3-cell battery and the carbon microphone M. On speaking to this microphone the electric potential of the grid of the control valve is varied in accordance with the wave form of the aerial speech waves, and this in turn fluctuates the plate or electron current in the control valve. These variations in the plate current are caused to affect in like manner the potential of the plate of the generating valve, and therefore the amplitude of the carrier waves emitted from the aerial. Accordingly we have the wave form of the speech sounds impressed upon the amplitude or height of the carrier waves and the transmitter

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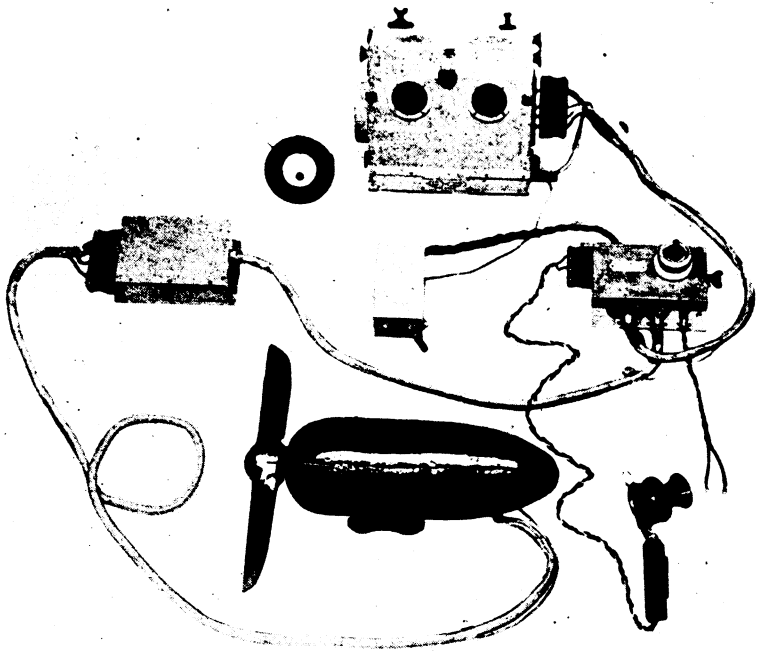
affects in like manner the current in the distant receiver circuits.

This plant is designed to operate with wave-lengths of 1,000 to 2,000 metres, and it is called a half-kilowatt plant because it employs about 500 watts in electric power to operate it. In more powerful transmitters the power valve is duplicated, or there may be three or more power valves, and two or more control valves. The necessary high voltage for the anodes or plates of these valves may be obtained from high voltage (1,000—2,000 volts) direct current dynamos, and in the case of aeroplanes the small high-tension dynamo is driven by a little windscrew or windmill, caused to rotate by the rush of the aeroplane through the air (see Fig. 95).

This dynamo may have two separate armatures, one providing a current of about 0·1 ampere at 1,500 volts for charging the valve anodes, and a low voltage armature providing a current of 5 amperes or so at 7 or 8 volts for incandescing the filaments of the valves.

An ingenious part of the equipment for aircraft in the aircraft plant of Marconi's Wireless Telegraph Co. is the arrangement of remote control, in which all the valves and supply circuits of the transmitting part of the arrangement are brought into operation merely by pressing a switch on the handle of the speaking microphone, which is the only part the aeroplane pilot or observer need touch, or has within reach.

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By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 95.—Aircraft wireless telephone set, as made by Marconi's Wireless Telegraph Co. In the centre of the diagram at the bottom is shown the small direct current dynamo, driven by a wind screw, which supplies the high plate voltage for the generating valves.

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The lay-out of apparatus shown in Fig. 95 gives some idea of the apparatus as installed in an aeroplane. Connections are made by means of heavily insulated cables having plugs at their extremities, the instruments to which the connections have to be made being provided with sockets to receive them. The transmitter is similar to an ordinary telephone transmitter in shape, with the exception that there is no receiver attached, its place being taken by the head receiver telephones worn in the operator's cap.

39. Reception of Wireless Telephonic Speech.

We have then to describe the arrangements in the practical receiving apparatus. The use of a single rectifying valve or a crystal in the receiving circuit, as already described, is only suitable for short ranges of 10 or 20 miles or so, from fairly powerful transmitters. In actual wireless telephony over great ranges it is necessary to employ amplifying valves to magnify the oscillatory currents in the receiving circuits.

We have already explained that this amplification can take place on the high-frequency currents set up in the aerial wire and associated circuits by the carrier waves, or it may be effected after rectification of the high-frequency currents into low-frequency or speech-frequency varying currents. The former is termed *radio-amplification*, and the latter *audio-amplification*. In the case of radio-

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amplification the feeble currents set up by the carrier waves in the aerial wire *A* (see Fig. 96), are caused to induce other similar currents in an associated and tuned coupled circuit, comprising a condenser *C* and inductance coil *S*. A three-

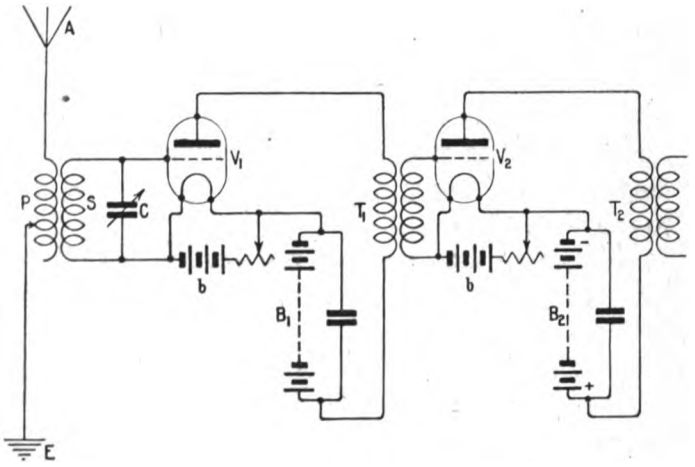


FIG. 96.—Arrangement of two or more amplifying valves for magnifying the feeble oscillations in the aerial wire *A*. V_1, V_2, are the thermionic amplifiers, T_1, T_2, the coupling transformers, and B_1, B_2, the plate batteries.

electrode valve has its grid and filament respectively connected to the terminals of the tuning condenser *C*.

The variations of potential thus produced in the grid cause similar changes in the plate current of that valve supplied by the high-tension battery as already explained.

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This plate current may include the primary coil of a transformer, consisting merely of two insulated wires wound on a bobbin, but without any iron core.

The secondary circuit of this transformer may have its terminal, connected respectively to the grid and filament of a second valve, and the same arrangements may be made for a third valve. If, then, the first valve and associated transformer magnify the grid-potential variations, say 5 times, the coupling of two valves and transformers will magnify it 25 times, and a third set 125 times, and so on.

We can in this manner use several amplifying valves for radio-amplification.

If we employ two-coil transformers, as shown in Fig. 96, we need then only one high-tension battery or dynamo to supply the high potential for the anodes or plates of all the amplifying valves. It is then necessary to explain in the next place the methods by which the three-electrode valve operates as a detector of oscillations. The reader will bear in mind that the carrier electric waves which arrive from the sending station are high-frequency electric waves of a certain wavelength and amplitude, or wave height. The effect of speaking to the microphone in the transmitting plant is to alter the amplitude of these waves, but not their wavelength. The amplitude varies in accordance with the wave form of the speech sound, so that we may

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say that the oscillations produced by the carrier waves in the receiving aerial consist of very rapid or high-frequency electric currents, which also have slow or low-frequency variations of amplitude superimposed. These slow variations of current correspond to the speech waves made at the sending end. The radio-amplification increases or magnifies these currents all in the same ratio.

We have then to impress these slow variations upon a receiving telephone. It would be no use, however, to insert a telephone receiver in the plate circuit of the last radio-amplifying valve, because a telephone receiver contains a coil of wire of many turns wound upon the iron pole pieces of a magnet. Such a circuit has a very large inductance, which means that rapid changes of current cannot take place in it. Hence the telephone coil will not permit the passage through it of a high-frequency alternating current. It offers too much *impedance*, as it is called, to such a current. Moreover, the mean value of these high-frequency oscillations of varying amplitude is constant. We have, therefore, to insert in the valve receiving arrangement a rectifying valve to change these high-frequency currents of fluctuating strength or amplitude into pulsating electric currents always flowing in one direction. This can be done by taking advantage of the form of the characteristic curve of the valve.

It has already been explained that when we give to the plate or anode of the valve a positive

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potential, electrons are drawn away from the filament, and this electron stream is generally increased by giving the grid a still greater positive charge. There is, however, a limit to this electron current, which is fixed by the temperature of the filament, and it cannot be increased beyond a certain amount at any given filament temperature. This limiting current is called the *saturation current* at that temperature. Corresponding to this saturation stage the characteristic curve has, therefore, a bend or change of direction. In the same manner, if we give the grid a gradually increasing negative charge, and thus steadily diminish the electron flow from the filament, we find the characteristic curve at the lower end bends over. Suppose, then, that we give the grid of a valve a negative potential, say about 4 volts compared with the filament, and then superimpose on this steady grid voltage a feeble high-frequency alternating voltage. It will be clear that when the small alternating potential makes the grid negative, the thermionic current or electron stream from the filament cannot be much reduced because the grid has already been made strongly negative. When the alternating potential applied to the grid is positive, then the electron stream is sensibly increased. The result, then, of imposing feeble alternating potential on the grid in addition to a steady negative potential is to increase on the whole the electron stream from the filament.

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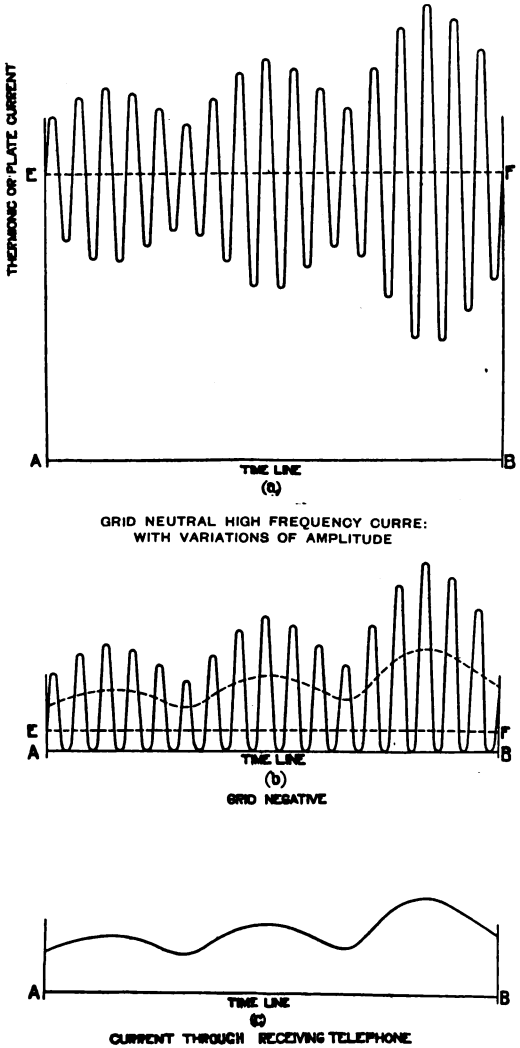


FIG. 97.—Diagrammatic representation of rectification and the mean value of the rectified currents which operate the diaphragm of the telephone.

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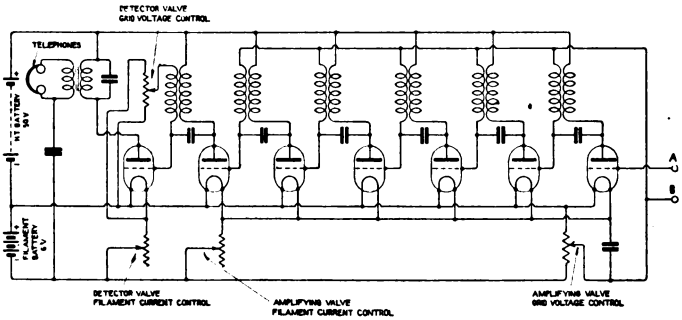
If, then, the alternating potential suffers changes of amplitude, as it does when the carrier electric waves are changed in height by speaking to the microphone in the transmitter, the electron stream of the detecting valve will experience similar increases in mean strength, although there are also rapid variations in the current. The actual changes produced in the currents will be best understood by a series of diagrams.

In Fig. 97 in the upper diagram (*a*) the ordinates of the curve represent the high-frequency current in the receiving circuit as magnified by the radio-amplification. This current has low-frequency variations of amplitude superimposed upon its high frequency, but the mean value of the current is always the same. The second diagram (*b*) shows the effect on this current of the detecting valve, the grid of which has a steady negative charge given to it. Since the electron current cannot then be much decreased, the effect of the additional negative charge given to the grid produced by the superimposed alternating potential is extremely small, but the effect of the positive charges is to increase the electron current.

The mean value of the current therefore fluctuates as shown by the ordinates of the dotted lines in diagram (*b*). If, then, the plate circuit of the detecting valve has included in it the coils of a receiving telephone, the rapid variations of current would produce no effect in the telephone, but the

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slow variations of the mean current cause the diaphragm of the telephone to vibrate, and its motions correspond to the slow or audio-variations in the amplitude of the carrier waves. Hence the receiving telephone will reproduce the speech sounds made to the transmitting microphone, the energy being conveyed by the carrier waves as above described.



By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 98.—Scheme of circuits of a seven-valve thermionic receiver with amplifying valves and detector or rectifying valve.

We can also employ one or more amplifying valves to increase the amplitude of the rectified low frequency speech current variations, which is termed audio-amplification.

For this purpose one or more three-electrode valves are placed after the detector valve, and have induction coils inter-connecting their grid and plate circuits exactly as in the case of the radio-amplifying valves. These induction coils or transformers may have cores composed of bundles of fine

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iron wires, which increases their effect, and has no disadvantage in the case of the transformation of low frequency oscillations. We can thus employ two or three audio-amplifying valves and put the telephone receiver in the plate circuit of the last valve, as shown in the diagram in Fig. 98.

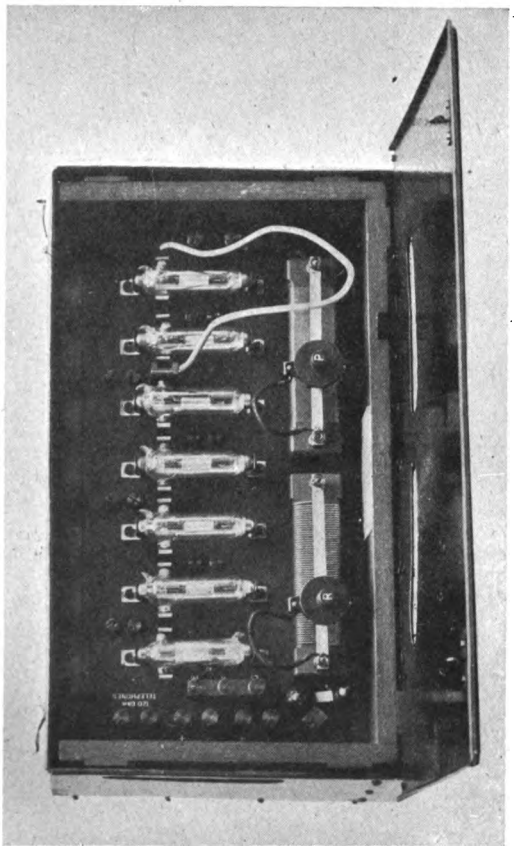
A multiple valve receiver may therefore comprise two or three radio-amplifying valves, a detector valve, and one or two audio-amplifying valves. The Marconi Co. have designed a seven-valve receiver, in which six of the valves are radio-amplifying, and the seventh and last valve the detector valve (see Fig. 99).

A simple form of valve-receiving circuit comprises a single detector valve, the grid of which is connected to one terminal of the tuning condenser in the receiving circuit, and also a single audio-amplifying valve with a telephone receiver in its plate circuit. The necessary negative potential is given to the grid of the detector valve by means of an arrangement called a *potentiometer*.

A long fine wire wound on a suitable support has its terminals connected to a few cells of a battery, which may be the filament heating battery. By means of a sliding contact we can connect a point on this wire to the grid, and by changing the position of this slider apply to the grid a negative potential, or two or three volts or more, as required,

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to bring the plate or electron current of the valve to that point on the characteristic curve which



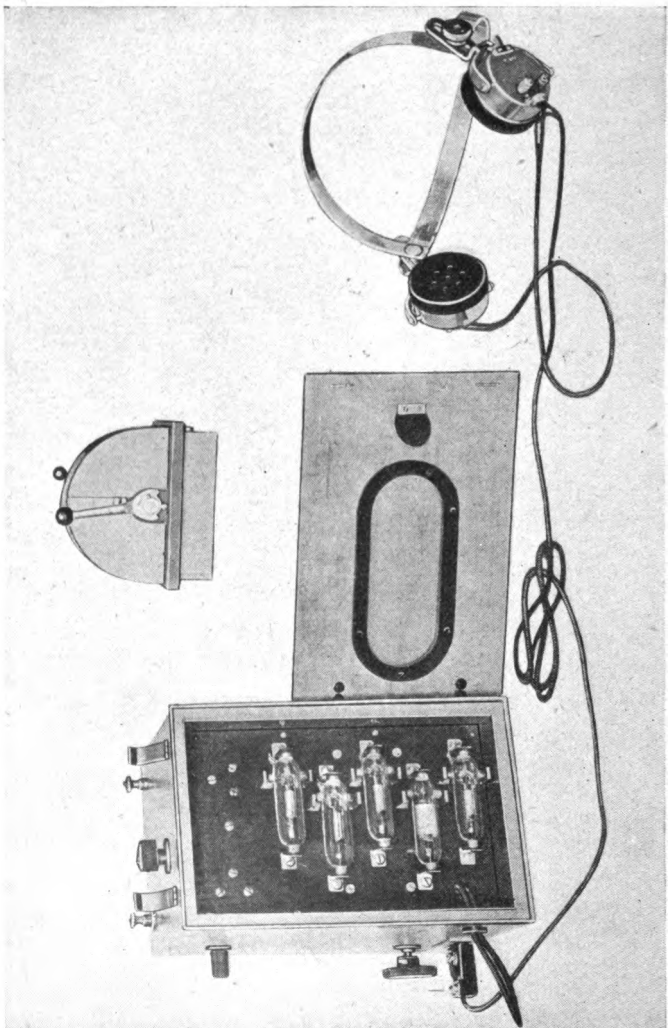
By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 99.—A view of a seven-valve receiver as made by Marconi's Wireless Telegraph Co.

corresponds to the beginning of the lower bend of the curve.

In order that telephonic speech may be trans-

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By Courtesy of Marconi's Wireless Telegraph Co., Ltd.

FIG. 100.—Aircraft receiving set comprising three high-frequency amplifying valves, a detecting valve and one low-frequency amplifying valve connected to the head telephones through an induction coil.

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mitted without distortion, it is essential that the radio-amplifying valves should have a characteristic curve which is nearly straight or flat in the central part. It is only under this condition that the complicated variations in the plate current will follow exactly the similar variations in grid potential, and hence amplify without distorting the wave form of the oscillatory currents. This result is achieved by certain precautions in the design of the amplifying valves.

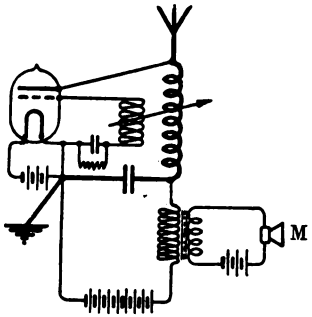


FIG. 101.—Circuits of a simple form of wireless telephone transmitter with the microphone *M* inductively connected to the plate circuit of the valve.

We have already explained that in a valve transmitter for wireless telephony there must be a valve, the plate and grid circuits of which are coupled inductively to produce high-frequency oscillations in the plate circuit and radiate carrier waves from an associated aerial as in Fig. 101. We have then to modulate the amplitude of these carrier waves by means of a carbon microphone in accordance with the wave form of the speaking voice. One way of doing this is by coupling a microphone *M* inductively, that means by means of an inductance coil or transformer, to the plate circuit of the generating valve as shown in Fig. 101. This method has

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disadvantages in practice. A better method of varying the amplitude of the carrier waves by means of the speech microphone has been called *choke control.* It has been found very suitable for the telephone transmitters of aeroplanes on account of its great simplicity.* It employs a power and a

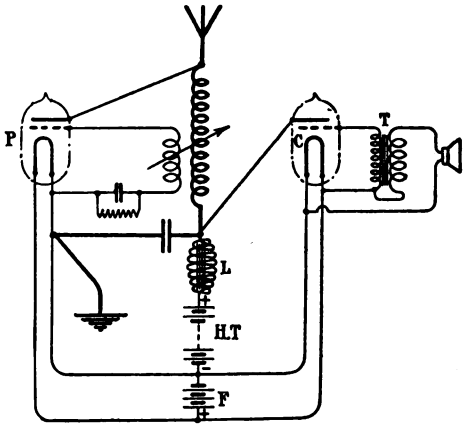


FIG. 102.—Arrangement of circuits in a wireless telephone valve transmitter called a "choke control" because it employs a choking coil *L* or large inductance.

control valve, which both derive their filament heating and plate currents from the same low- and high-voltage batteries (see Fig. 102). The plate or anode of the control valve is connected to one end of a large inductance or choking coil having an iron core, marked *L* in the diagram. The high-

* See Major C. E. Prince, O.B.E., "Wireless Telephony on Aeroplanes."—*The Journal of the Institution of Electrical Engineers.* Vol. 58, p. 377. May, 1920.

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frequency currents set up in the aerial wire by the power valve cannot pass through this choking coil, but find their way to earth through a condenser *C*.

The steady or direct current from the high voltage battery marked H.T. can, however, pass through the choking coil. When speech is made to the microphone the potential of the grid of the control valve is varied, and also low-frequency variations are produced in the plate current of the control valve. These changes of current strength produce large variations in the potential at the upper end of the choking coil *L*, which increase or diminish in a very marked and corresponding manner the plate current of the power valve. These surges react through the inductive coupling of the grid and plate circuit of the power valve upon the grid potentials. Hence the effect of speaking to the microphone is to make large percentage changes in the amplitude of the high-frequency oscillations set up in the aerial, and therefore upon the amplitude of the radiated waves.

40. Duplex Wireless Telephony.

Another matter of considerable importance in connection with wireless telephony is the arrangements necessary to allow the conversationalists to " cut in " and interrupt each other in course of a conversation. We know that when two people are conversing through a single speaking tube they have to be careful not to interrupt each other, for

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if both try to speak at once, or both listen at once, only confusion results. On the other hand, in the ordinary use of the exchange telephones we listen and speak at the same time. The listener can cut in with an interjection or question, or assure the speaker he is hearing, or ask for a word or sentence to be repeated. In the first forms of wireless telephony this cutting in was impossible. The aerial wire at each station had to be switched over from the transmitter to the receiver as required, and each conversationalist had to be certain his distant colleague was ready to listen before he began to speak. This difficulty is to some extent obviated by the use of two slightly different wavelengths for sending and receiving, and the separation of the sending and receiving stations at each post by a certain distance. This was done in the case of the wireless telephone demonstrations across the North Sea conducted by Marconi's Wireless Telegraph Co. between Southwold, on the east coast of England, and Landvoort, near Haarlem, in Holland, in 1921.

The distance between these two places is 112 miles. At each place a transmitting and receiving station was established about 700 yards apart. Let us call these stations T_1 and R_1 in England, and T_2 and R_2 in Holland. The station T_1 telephones to station R_2 with a wave of 98 metres wavelength, and the station T_2 transmits to R_1 with a wave 94 metres wavelength. This difference of wavelength

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(4 metres) was found to be sufficient to prevent the transmitter "jamming" the near-by receiver on the same side. At each transmitting station there was a valve transmitter made as above described, and a transmitting aerial 18 metres high, in which was created an aerial current of 5—8 amperes, which was modulated by an ordinary telephone exchange microphone.

The total power taken up by the transmitter was about 5 kilowatts, and of this 10 per cent., or 0·5 kilowatt, was radiated from the aerial in the form of carrier waves. Underground wires were brought from the receiving station to the transmitting station, so that the actual speech and hearing on each side of the sea was conducted from one place, and the receiving valves could have their filament currents and high voltage circuits switched on from the speaking station. In this manner ordinary telephonic conversation was carried on perfectly.

The problem of duplex wireless telephony, meaning by that the ability of the two conversationalists to speak and hear at the same time and "cut in" as they please, cannot be considered as completely solved by the two-wave and separate station system, because such method could not be applied in the case of aeroplanes or ships for want of space. Accordingly the problem has engaged much attention. The difficulty of it will be realised when it is noted that in many cases where wireless telephony is of the utmost importance, as

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in speaking to or by aeroplanes from or to the ground station, only a single aerial is practicable on the aeroplane, and therefore the act of sending sets up strong oscillations in it, which, if they have access to the receiving apparatus tuned for the same frequency, may completely jam the latter and set it out of order. Hence, the real problem is to find a method of connecting the receiving apparatus to the aerial in such a fashion that the strong oscillations set up on sending shall not have access to it.

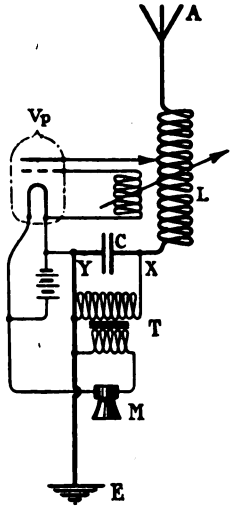


FIG. 103. — A type o quiescent aerial with valve transmitter in which the microphone *M* supplies the plate voltage in the act of speaking.

One solution which has been suggested, but which is only an imperfect solution, is that often called the quiescent aerial. In this case the permanent high-frequency oscillations are not maintained all the time in the sending aerial and modified in amplitude by the speech microphone on speaking, but the high electromotive in the plate circuit of the generating valve is applied only by the microphone when it is actually in operation by speech being made to it (see Figs. 103 and 104). The method, however, is not very successful unless

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a certain supplementary steady voltage is applied by a battery in the plate circuit of the generating valve. The reason for the imperfection is that the transformer in connection with the microphone takes a little time to build up the voltage in the plate circuit of the valve which is necessary to set up oscillations, and there is therefore a want of response unless there is a certain minimum of constantly maintained oscillations in the aerial, and the employment of these permanent oscillations defeats the very thing that it is desired to achieve, viz., the immunity of the receiver from the effect of the transmitter. We cannot, therefore, say that, as far as the confined space of aeroplanes is concerned, the problem of duplex telephony has been completely solved. As far as ground stations are concerned, it is worthy of notice that for not very great ranges with no very great differences in the

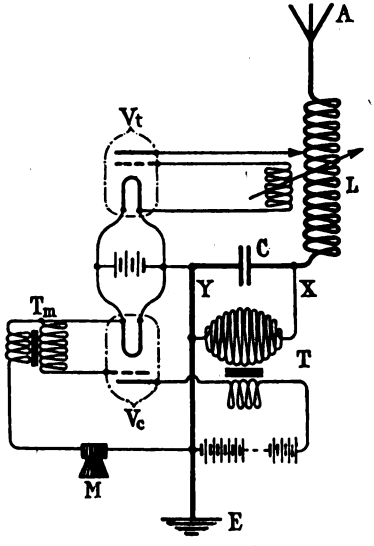


FIG. 104.—A type of quiescent aerial with valve transmitter. The microphone *M* controls the supply of plate voltage in the transmitting valve *Vt*.

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wavelengths—for example, two wavelengths of 110 and 113 metres, and the transmitting and receiving stations only 100 yards apart—it has been found possible to conduct good duplex telephony.

41. Directional Short-wave Wireless Telephony.

Another question of great practical interest in connection with wireless telephony is the employ-

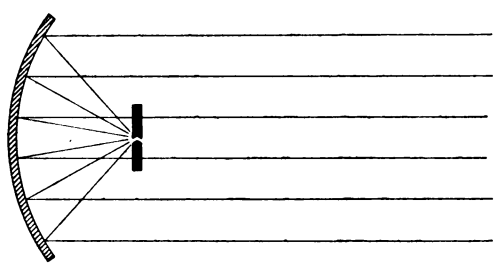


Fig. 105.—An electric arc lamp in the focus of a parabolic mirror projecting a parallel beam.

ment of very short electric carrier waves of a wavelength of only 12 or 15 metres, and of reflecting mirrors to make a beam of electric radiation like an electric searchlight. This "wireless beam" limits the lateral spread of the waves so that it conduces to privacy of speech. We have already explained in the section dealing with Hertzian waves that these waves can be reflected like rays of light from suitable surfaces.

In the case of an electric searchlight the arc lamp is placed in the focus of a parabolic silvered-glass

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mirror, and this reflects all the rays falling on it in a direction parallel to the axis of the parabola (see Fig. 105). In the same manner, if we bend a large sheet of metal round two formers of wood so as to make a parabolic cylindric mirror, and place a Hertzian linear oscillator on the focal line of the mirror, then, provided the dimensions of the mirror are not small compared with the wavelength, we shall project a beam of electric radiation, or of Hertzian waves, parallel to the axis of the mirror.

Experiments of this kind were made many years ago by Hertz and other physicists, and in the early days of wireless telegraphy Senatore Marconi employed parabolic mirrors in the initial attempts to use Hertzian waves as a means of signalling.

It is not, however, very easy to produce continuous electromagnetic waves for the purposes of wireless telephony of wavelength much shorter than 10 to 15 metres. It is essential then that the dimensions of the mirror should be something of the order of 20 to 30 metres. If mirrors of solid metal were employed, these would not only be heavy to move, but would offer such surface to the wind that they would be dangerous to erect. It has been found, however, that if a number of wires are stretched parallel to each other on a frame, and at a small distance apart, this grid will reflect electric waves if the electric force in the wave is parallel to the direction of the wires.

Accordingly we can make a parabolic electric

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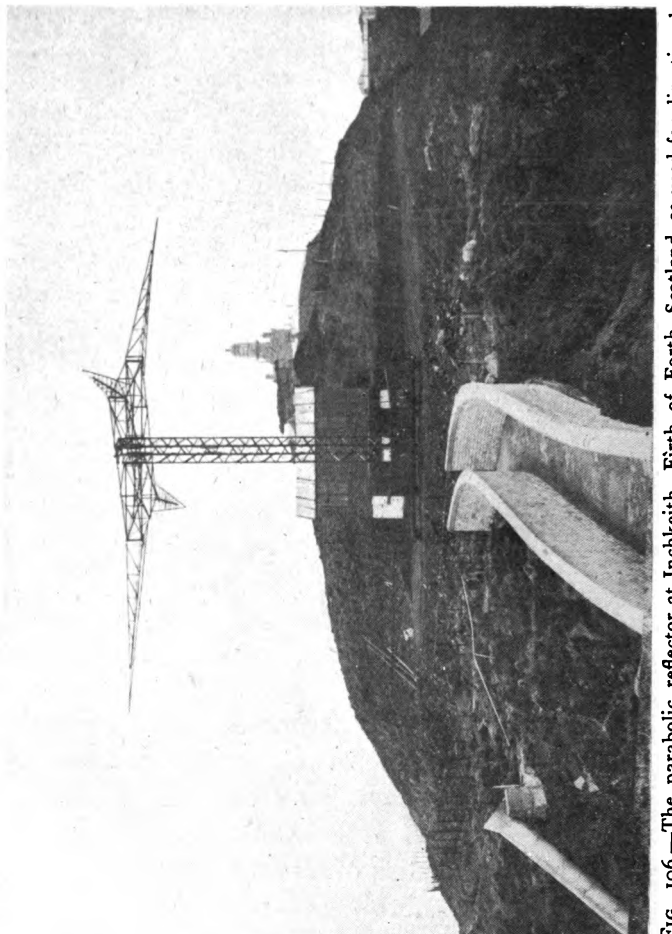


FIG. 106.—The parabolic reflector at Inchkeith, Firth of Forth, Scotland, as used for directional short wave wireless telephony.

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wave mirror which does not offer much surface to the wind as follows :—If we stretch a number of wires parallel to each other round the edge of two frames of parabolic form placed at a distance, the wires being held in such positions that they lie on a parabolic sectioned surface, and if we place parallel to these wires, and on the focal line of the parabolic surface, a Hertzian linear oscillator, we can project a wireless beam (see Fig. 106). It is easy to construct such skeleton parabolic reflectors of considerable dimensions, and since the wavelength of the waves radiated from a linear oscillator, or two rods placed in line, is about twice the total length of the rods, we only require a linear oscillator of about 25 ft. or so in length to radiate electric waves of 15 metres wavelength.

Parabolic reflectors of this kind, with linear oscillators in their focal line, have been employed by Mr. C. S. Franklin in important experiments made for Marconi's Wireless Telegraph Co. on directive short wave wireless telephony.* The carrier wave was 15 metres in wavelength, and the oscillations were generated by a couple of large thermionic valves having a power consumption of 700 watts, with 4,000 volts on their plate circuits, producing a plate current of 175 milliamperes.

* For a full description of these experiments the reader is referred to *The Wireless World and Radio Review*, of May 20th, 1922, Vol. 10, p. 219, and also to the Paper read by Mr. C. S. Franklin before The Institution of Electrical Engineers, May 3rd, 1922.

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These valves created in a linear, or Hertzian, oscillator, continuous oscillations of twenty million per second, and radiated a power of about 300 watts in the form of 15-metre electric waves. This oscillator was placed in the focal line of a skeleton wire parabolic mirror of about 30 metres aperture and a corresponding receiving aerial in the focal line of a similar reception mirror employed in reception by a usual amplifying valve detector.

After some preliminary and successful experiments at Carnarvon, a site was chosen at Hendon, and another at Frankley, near Birmingham, in February, 1921. These stations are 97 miles apart. With this plant telephonic speech was well conducted. Measurements indicated that the energy received with the directive mirrors up was about 200 times greater than when the mirrors were not used. Also it was found that very decided limitation to the lateral spread of the waves was obtained, so that places much outside the line of transmission could not overhear the speech.

It is quite practicable to employ still shorter wavelengths of less energy. Carrier waves, even as short as 4 metres in length, have been used for such reflector transmission of telephonic speech over seven miles. It is expected that the employment of this " wireless beam " in nautical wireless telephony will prove to be of great utility in giving ships direction and location during fogs.

As this little book is intended to deal only with

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the elementary principles of the subject, and to be within the range of knowledge of the general reader or would-be amateur in wireless telephony, it is not possible or necessary to extend it to cover highly technical matters, such as long distance wireless telephony, or the influence on it of such factors as soil absorption or atmospheric disturbances, which are sufficiently treated in various text-books.

42. Wireless Telephone Transmitters.

We may, in conclusion, make a brief reference to the construction of large transmitters intended for broadcasting and to improvements in thermionic valves employed as generators of powerful oscillations. No other type of generator is at the present time so suitable for this purpose. High-frequency oscillations of great power can be produced by dynamo machines called high-frequency alternators, but the regulation of their speed, which is necessary to produce carrier waves of perfectly constant wavelength and amplitude by them, requires some rather complicated apparatus, and it is not nearly so easy to modulate the amplitude by a speech microphone as is the case with the thermionic valve. Again, we can produce oscillations by means of an electric arc of a certain kind called a Poulsen arc, but this type of generator is liable to irregularities which, though not seriously disadvantageous to its use as a generator of oscillations for radiotelegraphy, are a

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decided impediment in the employment of it as a generator in wireless telephony.

The thermionic valve, on the other hand, gives or can be made to produce oscillations of perfectly pure simple harmonic wave form and, therefore, carrier waves of the same type.

Furthermore, the thermionic valve as a generator of oscillations is perfectly silent, and the amplitude of the oscillations produced by it very easily controlled by the speech microphone. It is for all these reasons an ideal oscillation generator for wireless telephony.

We have already described in a previous section the manner in which the three-electrode valve is employed to create electric oscillations, and these explanations need not be repeated here.

There are, however, great differences in construction and power consumption between valves used as amplifiers and valves used as generators of oscillations, which must be explained. The valve as a generator must have a considerable output of power, that is, we must be able to draw off from the circuit connecting the plate or anode of the valve and the filament an amount of electrical power which is only limited by our requirements. This implies that the so-called plate current must be, relatively speaking, large.

But the internal resistance of the valve, that is, of the space between the filament and anode cylinder, is also large, amounting to some thousands of ohms,

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generally speaking. Hence, it requires a high voltage to drive the required plate current across the vacuous space that is to compel the negative electrons to move away from the filament, and through the apertures in the grid, and strike the plate or cylinder.

Then again, this impact of torrents or millions of electrons bombarding the anode cylinder or plate heats it very quickly and may, in fact, soon make it red hot. Hence, special construction is necessary to prevent this heat from cracking the glass or loosening the sealing-in wire which makes connection between the anode cylinder and the external plate circuit.

On referring back to Fig. 93, which shows the view of a large transmitting valve of a very usual type, it will be seen that there is a large glass bulb, which may be even of the size and shape of a Rugby football, that has two re-entrant glass tubes at the ends which are closed at the inner ends and at the outer ends are sealed to the bulb.

Around these re-entrant tubes are clamped metal collars, one of which carries the large cylinder made of sheet nickel which forms the anode, and the other of which in a similar manner carries the inner cylinder of nickel wire gauze which forms the grid of the valve. This latter re-entrant tube carries also the tungsten wire filament.

The current is conveyed to and from this filament by platinum wires sealed through the glass tube, and

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similar platinum sealing-in wires are employed to connect the external circuits to the cylinder and the grid. The filament wires have to carry fairly large currents up to 10 or 20 amperes, but the sealing-in wire to the cylinder has only to carry currents from about one-tenth to one ampere or so, and the grid requires feeding with a much smaller current.

The electric power is supplied to the valve in the form of direct current. Direct current at rather low voltage, 20-25 volts or so, is employed to incandesce the filament. Direct current at high voltage, 1,000 to 10,000 volts or so, is supplied to the plate circuit to create the electron stream. We then draw off from the plate circuit high-frequency alternating current.

In large valves 70 to 80 per cent. of the power supplied can in this manner be recovered. The deficit is expended as heat in the valve. Hence, a large valve yielding, say, 5 kilowatts or 7 horse-power, would take in 7 kilowatts or 10 horse-power, and the difference or 2 kilowatts, is transformed into heat.

This heat must be radiated, and therefore large valves get fairly hot. One of the problems connected with large valve manufacture is to obviate any danger from the cracking of the bulb, which is liable to happen with glass bulb valves.

It must be remembered that these valves have to be very highly exhausted of their air, in order that no sensible amount of air may be left to be ionised by the electrons emitted by the filament, for this

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would create positively electrified ions or molecules of oxygen or nitrogen which have lost an electron, and these would be attracted to the filament very strongly, and would bombard it and soon destroy it.

It would occupy too much space to describe the methods by which the extremely high vacuum required is made in these valves. One result of this, however, is to create a very great air pressure on the outside of the bulb which, in a large valve, may amount to two or three tons. Hence, if such a valve breaks, it generally does so with a rather startling explosive noise. Invention has, therefore, of late years, been directed to the problem of constructing a high-power valve which shall be less fragile and liable to accidents than a glass bulb valve. In other words, to make a valve which shall be more of an engineering job than the present glass bulb type.

It has been found possible to make the bulb of pure silica (flint) in place of glass. This material has so small an expansion with temperature that a silica bulb can be made red hot, and then be plunged into cold water without cracking.

A still more important improvement, however, has come to us recently from the United States in the form of a thermionic valve, of which the greater part of the bulb is formed of sheet copper. The copper not only forms part of the bulb but also constitutes the anode cylinder, and can be kept cool by cold water.

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The foundation of this improvement is the technical discovery of a method of sealing copper to glass in such fashion that it does not crack away on cooling or subsequent heating.

The reason the expensive metal platinum has hitherto been used for wires which must be sealed air-tight through the wall of a glass bulb is that it possesses three essential qualities for this purpose. First, it has nearly the same coefficient of expansion with heat as lead glass. In the second place, hot platinum is "wetted" by molten glass; that is, sticks to it, and, lastly, platinum is not oxidised when heated in a blowpipe flame, but retains a bright and clean metallic surface.

No other metal has been found which possesses all these properties, but the discovery was made some years ago that if copper is kept unoxidised in a flame containing reducing gases it is, when very hot, "wetted" by molten glass, which sticks to it. Copper, however, has not the same coefficient of thermal expansion as glass, and the only way to attach a copper tube to a glass tube of the same size is to give the copper a sharp knife edge.

If, then, a sort of copper thimble is made, closed at one end, but with the edge of the open end made sharp like a knife, this thimble can be sealed air-tight to a glass tube of the same diameter as the thimble, and the joint will not crack away in cooling and can be made vacuum-tight. The glass tube terminates in a re-entrant portion through which are sealed

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wires, to which are sealed the wires which carry the

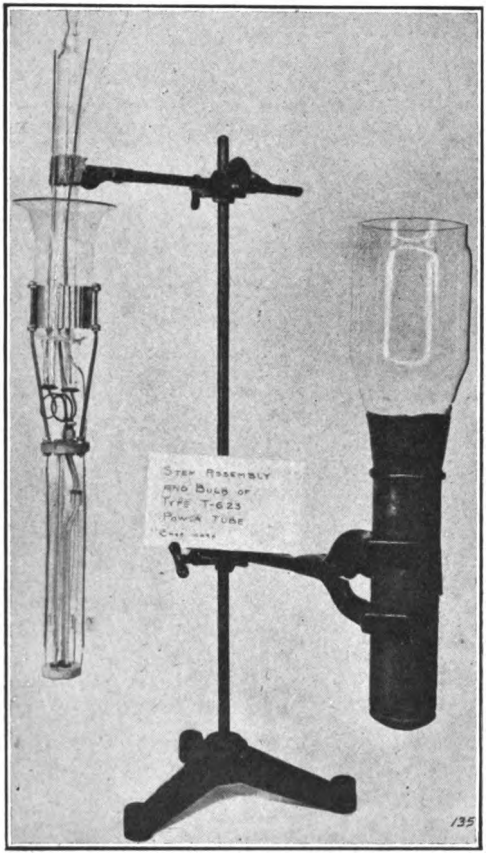


FIG. 107.—The arrangement before sealing in the re-entrant glass tube carrying the filament and the grid.

ends of the filament of the valve and also the leading-in wire for the grid.

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Fig. 107 shows the arrangement before sealing in the re-entrant glass tube carrying the filament and the grid. Fig. 108 shows the completed instrument. The copper tube part (shown in black in the diagrams) forms at the same time the anode cylinder, and also part of the bulb.

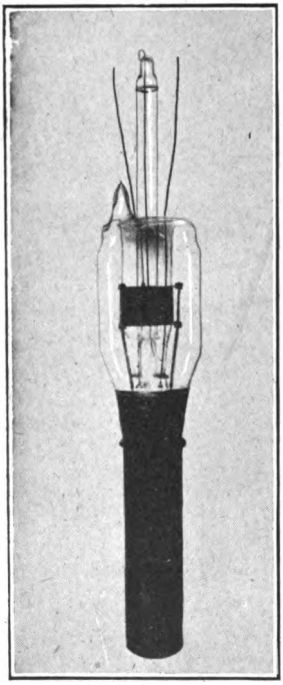


Fig. 108.—The complete instrument.

Externally it is surrounded by a water jacket, as shown in Fig. 109, by which it is kept cool by circulating water.

Valves of this description, of a size to yield 10 and 20 kilowatts output or 14 horse-power, have been already made, and valves to yield 100 or 150 kilowatts may soon be obtainable. At the present time broadcasting in connection with wireless telephony is conducted by large valve transmitters comprising a number of glass bulb valves, which are connected so that their plate currents are added together.

In our frontispiece is shown a view of one of the latest types of broadcasting valve transmitters,

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designed by Marconi's Wireless Telegraph Co. In Fig. 110 is given a view of the valve transmitter in the Eiffel Tower radio station in Paris.

The high voltage required for the plate currents is obtained by rectifying, by means of two-electrode valves as already explained, a low-frequency alternating current of high voltage (7,000 to 10,000 volts). A special form of microphone, such as is used in an ordinary wire telephone, is employed to modulate the grid potentials of one or more three-electrode valves called the control valves, and the correspondingly modulated plate current of the control valves, which fluctuates in accordance with the wave form of the speech sounds made to the microphone, is employed to modulate the output current of the generator valves. The result is that the height or amplitude of the carrier waves radiated from the sending aerial fluctuates also in accordance with the speech currents sent through the microphone.

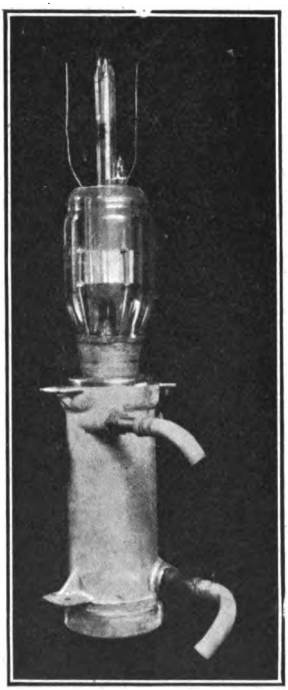


FIG. 109.—The valve anode inserted in a water cooling jacket.

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We have already explained the manner in which these radiated waves create corresponding but much

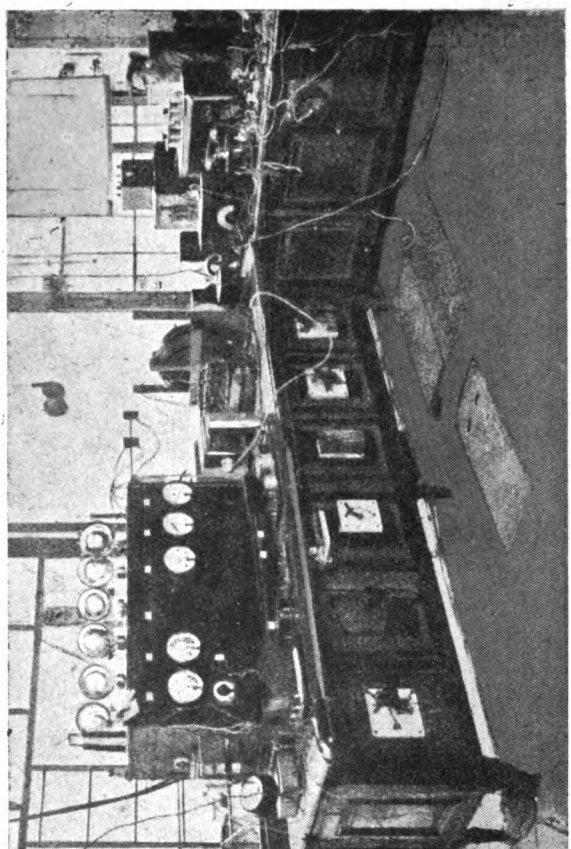


FIG. 110.—The Eiffel Tower wireless telephone broadcasting station with valve transmitters.

feebler currents in the receiving aerials, and are made to reproduce the speech sounds in the receiving telephones.

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We may, perhaps, in conclusion, offer a few words of advice to those who, having become interested in this fascinating subject, desire to avail themselves of the broadcasting facilities, and "listen-in" to the radiated speech and music.

The would-be listener-in must, of course, first provide himself with a Post Office licence, either for simple reception by licensed apparatus or an experimentalist's licence for certain other permitted operations.

The next point for consideration is the type of receiving apparatus to be obtained.

This must be determined by the distance and power of the broadcasting station from which the service is given, and, we may add, by the depth of the purchaser's purse.

A comparatively simple, and therefore cheap equipment will do useful service if within a few miles of such station, but for large distances a more sensitive and therefore expensive receiving arrangement is required.

Then, again, there is the question of surroundings to be considered. If the receiver is to be located in the middle of a large town where it is surrounded by high buildings, especially those with metal roofs or built with steel frames and girders, then there is a large absorption of energy, and therefore a weakening of the arriving wireless waves. Most large modern buildings are constructed of a mass of steel joists and girders, vertical and horizontal, and with

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concrete floors. Also pipes for water and gas, and wires for electric lighting are included. All this vertical and horizontal metalwork causes great absorption of the energy of the electric wireless waves, especially those of rather short wavelength, such as 300 to 400 metres.

On the other hand an isolated old-fashioned brick and timber house, right out in the country, is not subject to these deleterious effects.

Accordingly, a receiver placed in the midst of such energy-absorbing buildings will have to be more sensitive, other things being equal, than one in a more advantageous position.

Lastly, we have to consider the facilities for erecting an aerial wire. There are two main types of aerial :—

(1) An open wire aerial, and

(2) A closed circuit or frame aerial.

The first type consists of a wire or wires which may be a bare single, or, better, stranded copper wire, the lower end of which is connected to that terminal of the receiving apparatus marked " aerial," and the further end attached to an ebonite or porcelain insulator placed in some elevated position. The wire must not touch any wall, roof or tree in its course.

The best arrangement when possible is to erect a flagstaff or small yacht mast in the garden of a house, or on the roof of your house or some neighbouring building, and stay it with stout ropes, and then to fix to the top an ebonite insulating rod, to the

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end of which is attached the wire, or, better, a pair of parallel wires, kept about four feet apart by wooden

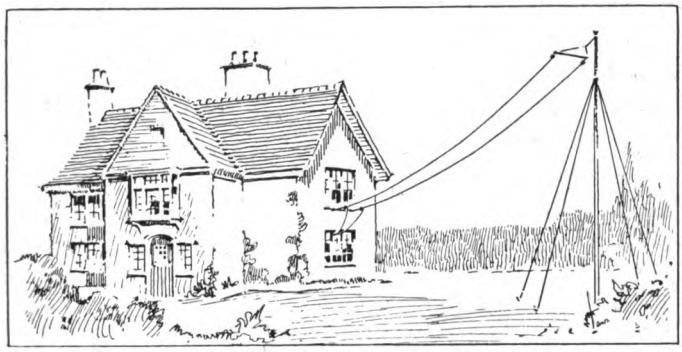


FIG. 111.—An outdoor aerial, consisting of a couple of parallel wires extending from the window of a house to the top of a mast in a garden.

spreaders. The lower ends of these wires may be brought in through an ebonite tube fixed in a wall or window frame so that the receiving apparatus is within the house (see Fig. 111). This is called an outdoor aerial. A frame aerial consists of a number of turns of wire generally insulated, wound on a square frame or cross of wood (see Fig. 112). This frame is supported so that its plane is vertical and can be turned round a vertical axis in any direction. This has the peculiar property that it receives most strongly waves travelling in the direction of its own plane. Hence it can be used as a

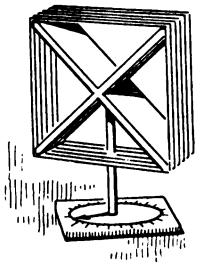


FIG. 112.—A frame aerial.

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directional aerial. The frame aerial is less sensitive, generally speaking, than the outdoor or wire aerial in catching wireless waves, and hence requires a more sensitive receiver, but it has the advantage that it is much less sensitive to vagrant atmospheric waves.

In the case of lofty rooms or public halls or churches, it is sometimes possible to erect an indoor aerial wire by stretching two or three wires horizontally across the room some little distance below the ceiling, the ends of these wires being connected to insulators, such as ebonite rods, which are attached to fixed points on the walls. From these horizontal wires a down leading wire can be brought to the receiver, making what is called a T aerial.

The ceiling, however, should be free from steel joists or metalwork.

Having obtained a licence and erected an aerial, the would-be listener-in will then require receiving apparatus. Let him or her be content with small achievements first, and learn to manage simple apparatus before attempting to use more complex appliances.

The first step is to understand the limitations of various sets, and not jump to the conclusion that with a cheap crystal detector set and pair of indifferent telephones he can pick up speech or music from very distant stations all over Europe.

The essential element in all receiving sets is a pair of good head telephones made by a firm with a

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reputation. It is not desirable to unscrew ear-pieces or take receiving telephones to pieces, to see how they are made, or else it will not be easy to readjust them.

If the licensee is so fortunate as to have his receiving point not more than 10 or 15 miles from a broadcasting station, then it will be best for him to begin operations with a crystal receiving set and an outdoor aerial. The set includes a tuning coil or aerial inductance, a variable condenser, a rectifying crystal and a pair of high-resistance head telephones. There are two terminals, one of which is connected to the base of the aerial wire, and the other by a thick bare copper wire to the nearest water tap or pipe. For adjustments the maker's instructions must be followed. Do not, however, expect too much of such simple appliances.

For a listener whose nearest broadcasting station is distant, say by 50 miles or less, a two- or three-valve thermionic receiver set will be necessary when using an outdoor aerial. One of these valves constitutes the high-frequency amplifier, the second the detector, and the third the amplifier. The inexperienced user must then proceed cautiously and follow carefully the instructions of the maker or those in numerous little practical handbooks which have been published.

The valve is only a kind of electric lamp, and any mistake in putting too high a voltage on the filament will result in a burn-out, and then a new valve will

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probably cost 15*s.* to 17*s.* 6*d.* The set requires separate filament heating storage batteries and plate batteries, which must be re-charged as required.

For still longer distances a multivalve set is necessary. For details as to construction and management of these complicated receivers, and for the combination with them of loud-speaking telephones, special manuals must be consulted, and the user will only acquire the necessary skill to handle such sets by painstaking work and the careful study of wireless literature.

The best advice to the beginner is to join a local wireless society, and pick up from more experienced amateurs the necessary knowledge to get the best out of any receiver he can afford. He will in that way learn much which is not contained in any book, and the vagaries of " atmospherics," the difference between day and night reception, sunrise and sunset effects, and the peculiar phenomenon called " fading " will become familiar to him, while the acquirement of skill in tuning-in or avoiding " jamming " will bring continual fresh interest. It is a wonderful art which has thus been evolved in the last ten years or so.

The development of wireless telephony is, indeed, one of the fairy tales of science, in which the wonderful thermionic valve takes the place of a modern Aladdin's lamp, annihilating space and making the whole of this terrestrial globe one vast auditorium, in which a single voice can influence, for

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good or for evil, untold thousands of listening human minds.

The development of wireless telephony, and especially the public use of broadcasting, introduces a new factor into modern life which is bound in time to make its effect felt.

The purpose of this little book will have been fulfilled if the broad general principles of the art have been elucidated sufficiently for the instruction of the general reader.

THE END.

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